Development of High I_c Ex Situ Processed YBCO Coated Conductors

Home

Help

Summary

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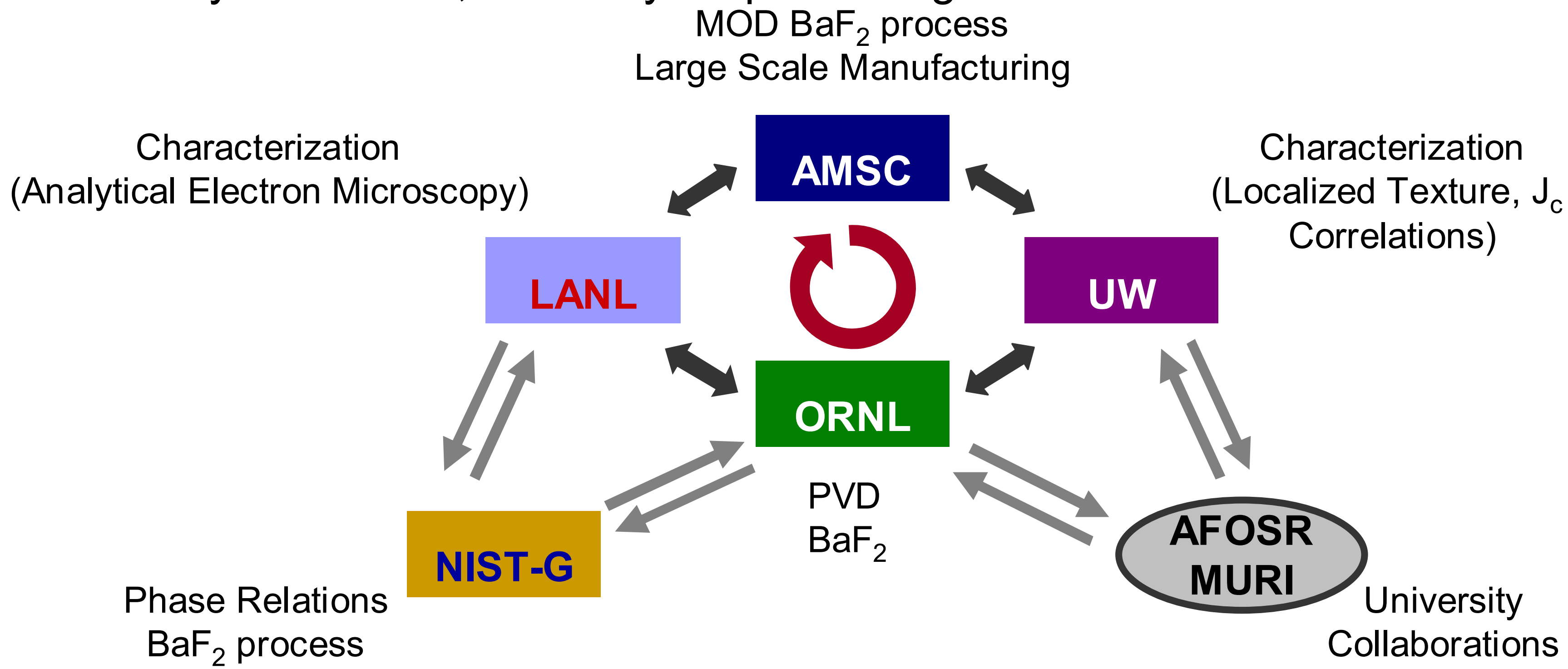
Industrial partner: American Superconductor Corporation

Funding: ORNL: 225 k$ (DOE)
LANL: 200 k$ (DOE)
UW: 200 k$ (DOE, AFOSR-MURI)

Multi-institutional research group with the experience and expertise to focus on ex-situ processing of YBCO films.

- Grouping of existing collaborations and expertise into an effective collaboration.
- Third year of work, second year presenting at DOE annual review.



A focused purpose and set of objectives helps guide research directions and facilitate year over year advancements.

- Purpose and Motivation
  - To advance a materials science background for *ex situ* processing of high-performance ReBCO coated conductors
  - Long-term goal: Increase I_c to 1000 A/cm at 77 K
    - consistent with 2003 DOE Coated Conductor Roadmap
    - enable broad implementation of CCs
    - reduce cost/performance ratio: $ / kA-m

- Long-term objectives are to develop understanding of:
  - Fundamental epitaxial growth mechanisms (*ex situ* BaF_2 process)
  - Connectivity and the thickness dependence of J_c
  - Origin of flux pinning in high J_c ReBCO coated conductors

Several significant advancements in understanding *ex situ* YBCO film development were made in FY2004.

- Understanding of liquid phase development, laminar growth, and high-J_c structures
- Grain boundary meandering and grain boundary overgrowth
- Fast processing (> 10Å/s) of ex-situ YBCO films
- Performance improvement year over year
  - **FY2003:** **235 A/cm-w (J_c = 0.94 MA/cm^2)** with film thickness 2.5 µm on an ORNL RABiTS™ template.
  - **FY2004:** **400 A/cm-w (J_c = 3.3 - 2.4 MA/cm^2)** with film thickness 1.2-1.7 µm on an AMSC RABiTS™ template.

Outline of Talks

Terry Holesinger	Liquid phase formation, laminar growth, and microstructural development of high-J_c *ex situ* films.
Matt Feldmann	Through-thickness grain structure: grain boundary complexity in thick *ex situ* films
Ron Feenstra	Processing for high I_c *ex situ* YBCO coated conductors (PVD-BaF_2 process).

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

PVD-BaF_2: Physical vapor deposition of precursors

American Superconductor

MOD-BaF_2: Metal organic deposition of precursors

Liquid phase formation, Laminar growth, and the Microstructural Development of High-J_c *ex situ* YBCO films.

Terry Holesinger

Synopsis

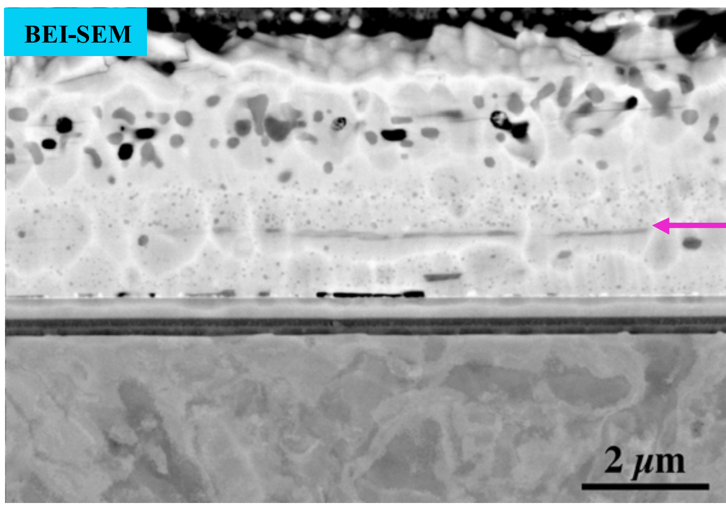
A microstructural summary is presented of a bi-modal structure in PVD-BaF_2 ex-situ films that forms under a certain set of standard processing conditions, the causes for its formation, and variants of this structure and their relationship to the performance level of the films.

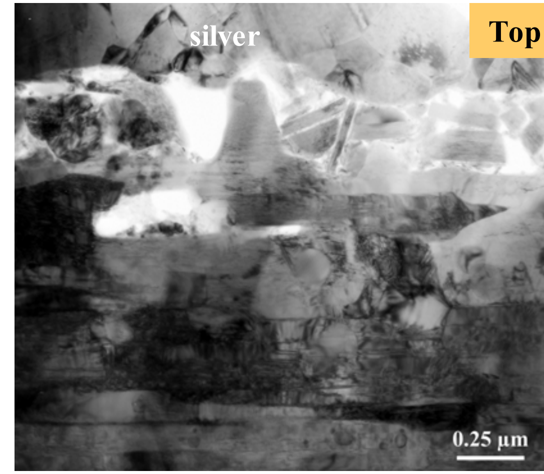
The amount of liquid phase formation and porosity during processing plays a pivotal role in determining the microstructural uniformity, second phase assemblages, grain boundary structures, and ultimately the resulting performance levels.

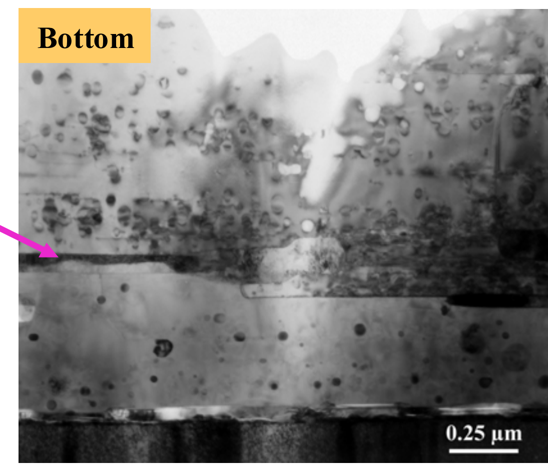
Based on these insights, new processing routes have been developed that have allowed for faster conversions, uniform microstructures, and higher performance.

The "standard" conversion of PVD-BaF_2 YBCO films produces high-J_c films with a bi-modal microstructure.

- Bi-modal: Large, well formed YBCO grains in bottom half of film and smaller, faulted YBCO grains in the top half.
- Structure indicates two different growth modes.
- Distinguishing microstructural features.
  - Laminar growth mode.
  - $Ba_2Cu_3O_y$ or Ba-O-F second phase layers.
  - Large YBCO grains with layers of Y_2O_3 precipitates.







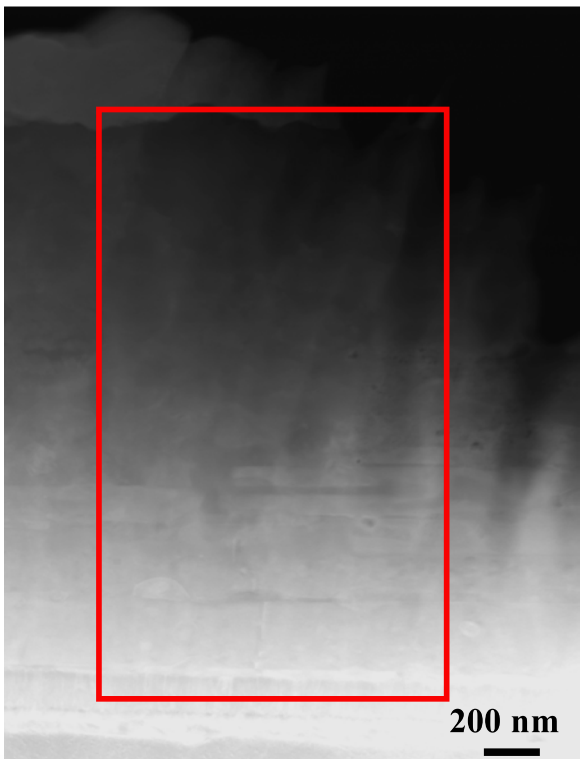
Second Phase Layers

RABiTS™ Template with 5 μm PVD-BaF_2 YBCO film
J_c(77K) = 0.31 MA/cm^2 155 A/cm-width

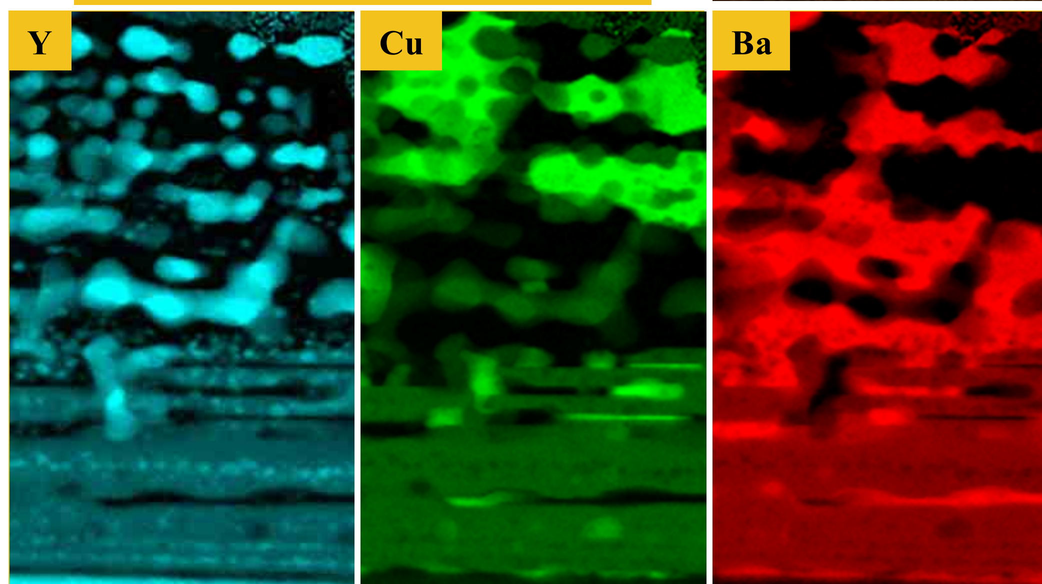
IBAD YSZ (LANL) / CeO_2 / BaF_2 YBCO (ORNL)
J_c(77K) = 0.93 MA/cm^2 / 2.9 μm YBCO film / 270 A/cm-w

The bimodal structure is generated by several events that occur in the early stages of conversion.

- CuO segregation
- Excess liquid phase generation
  - Y_2O_3 particles floating in the Ba-O-F near growth front.
  - (3) $YCuO_x$ + (2) Ba-O-F $\rightarrow$ $YBa_2Cu_3O_y$ + Y_2O_3
  - Layered Y_2O_3 structure within the large YBCO grains in bottom half of bimodal structure.

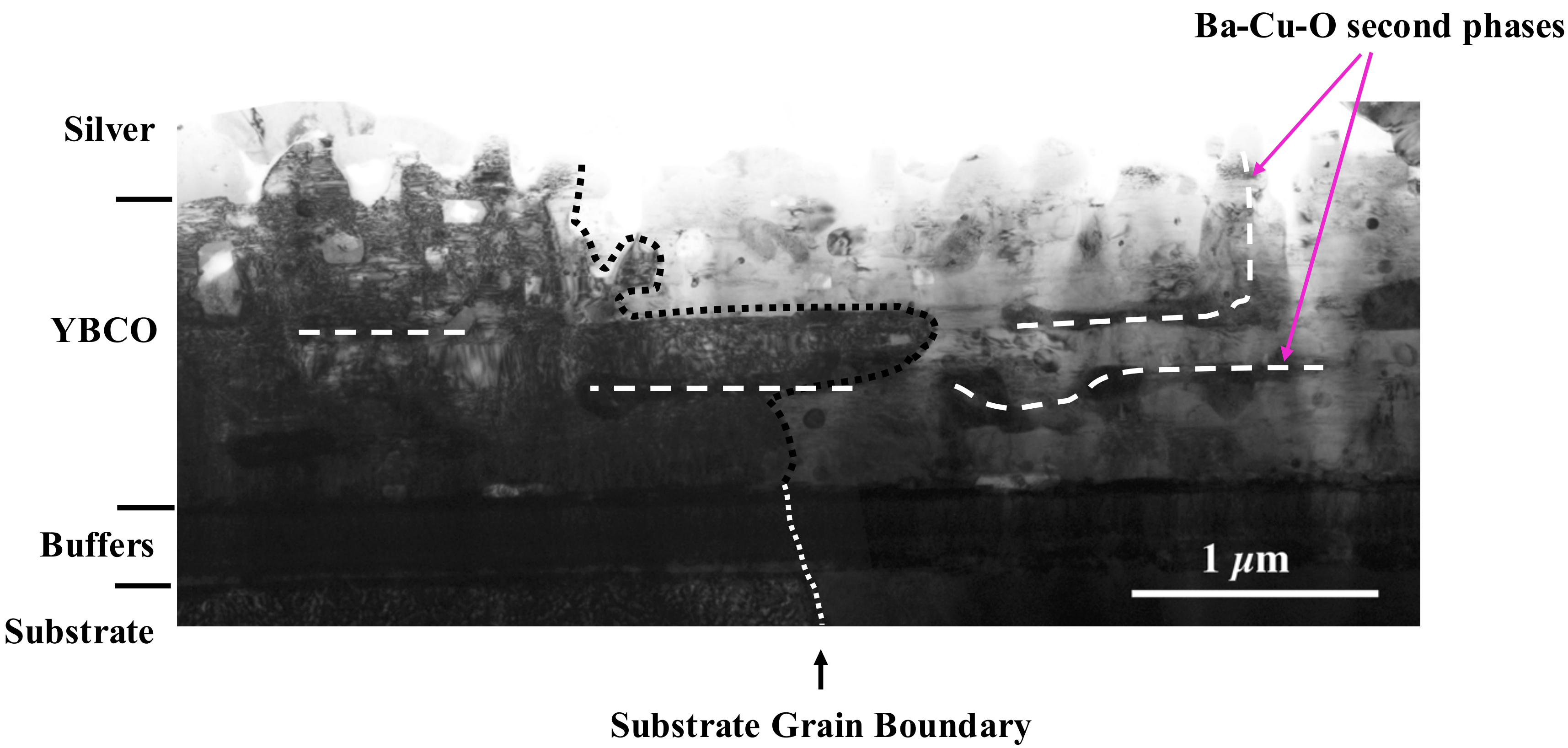


2.66 µm film on RABiTS quenched after 1.5 hours total processing time



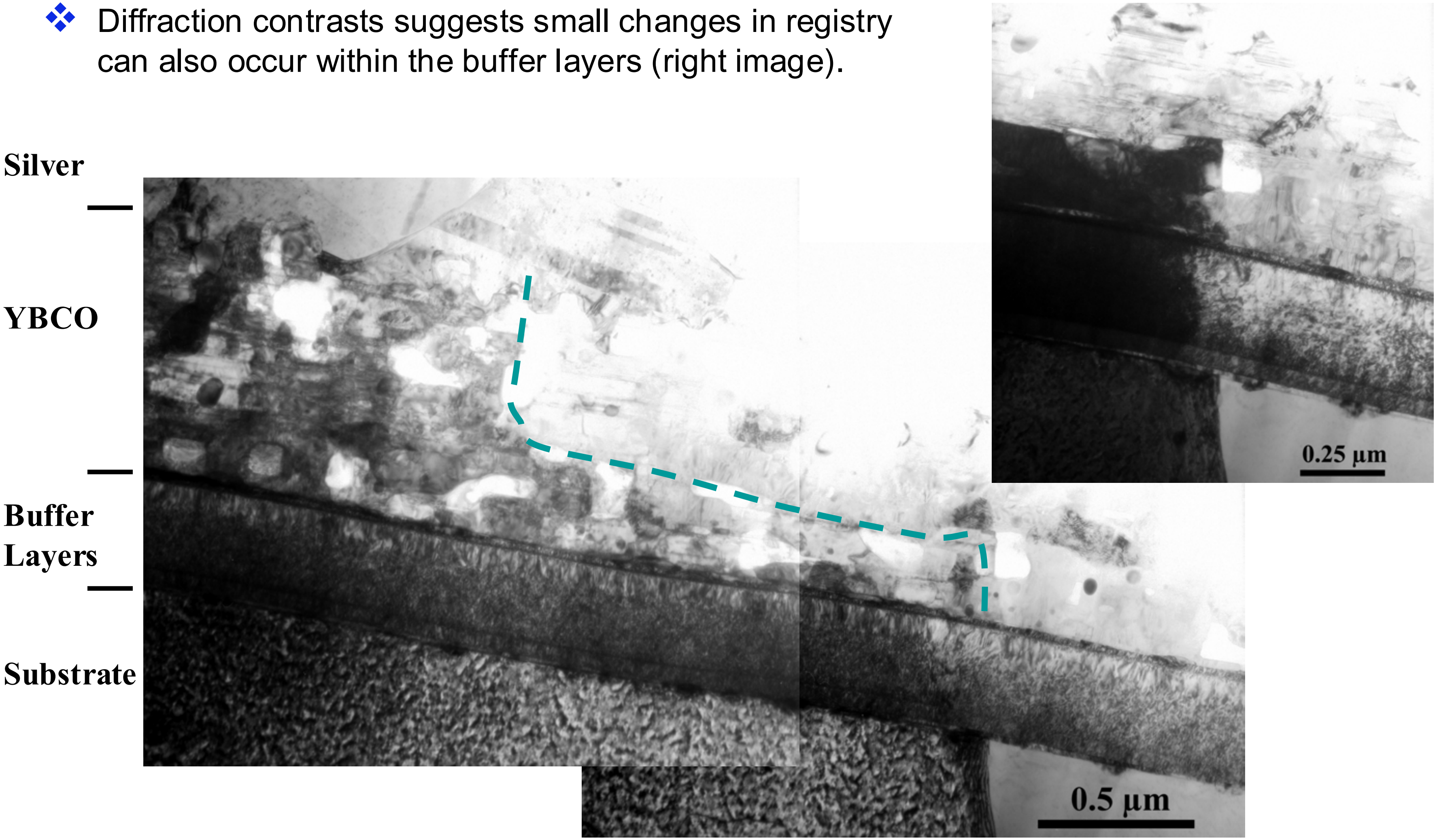
The laminar growth mode of *ex situ* YBCO grains manifests itself in the structures above RABiTS™ substrate grain boundaries.

- Grain boundary meandering may have important ramifications for connectivity and J_c performance levels.

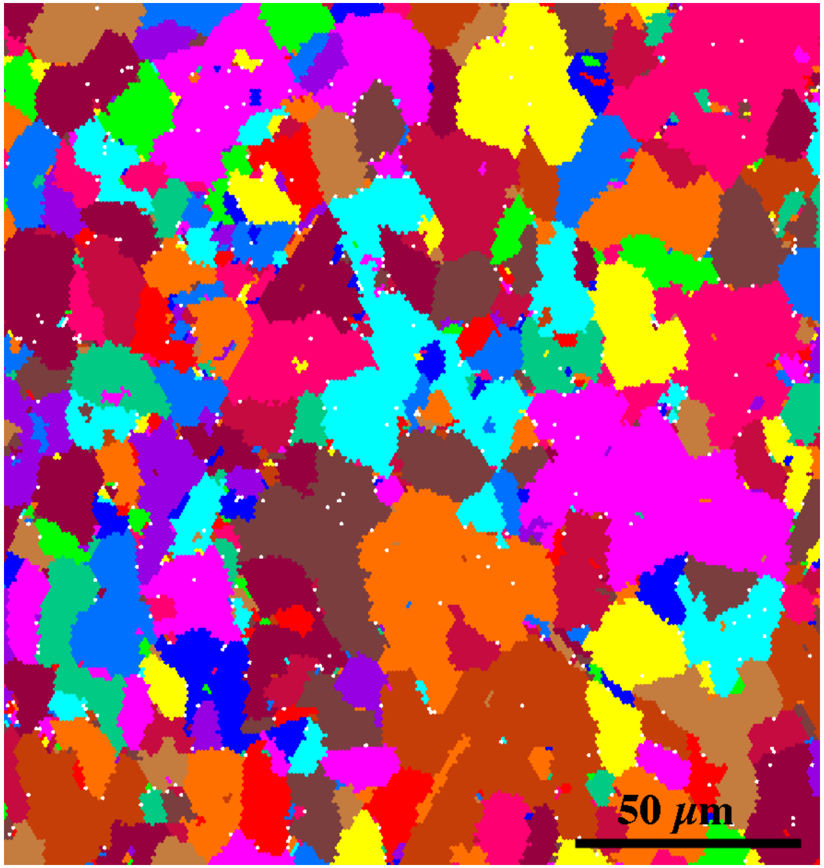


Grain boundary meandering above substrate grain boundaries also occurs in MOD YBCO films.

- Diffraction contrasts suggests small changes in registry can also occur within the buffer layers (right image).



Liquid phase assisted growth is evident from the large YBCO grains that can form as shown by EBSD and TEM.

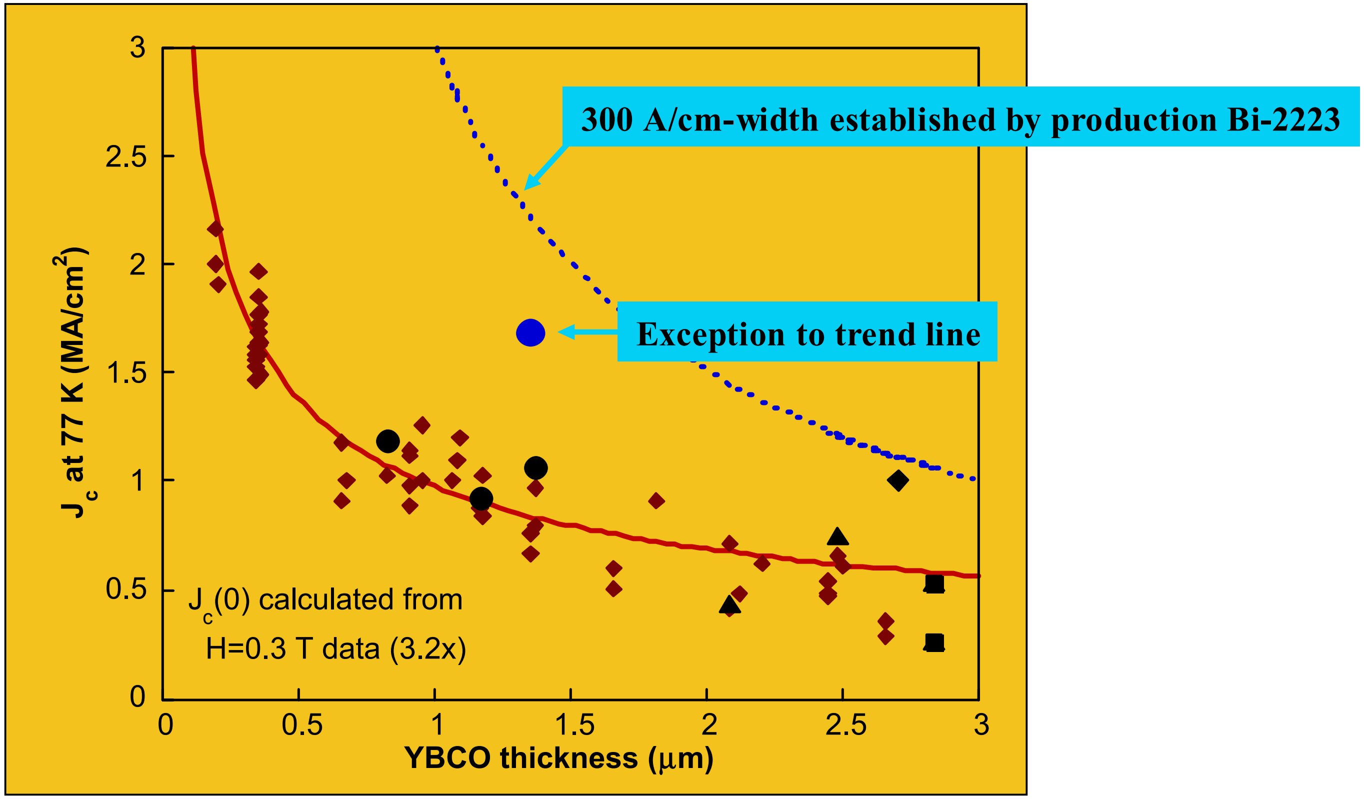


IBAD YSZ (LANL) / CeO_2 / BaF_2 YBCO (ORNL)
J_c(77K) = 0.93 MA/cm^2 / 2.9 μm YBCO film / 270 A/cm-w

- YBCO grains up to 50 μm in size were observed by EBSD and TEM.
- The IBAD YSZ template has a grain size of ≈ 0.1 - 0.25 μm.

YBCO films converted with the "standard" process (bi-modal structure) will not meet needed performance levels.

- Need to modify processing to increase J_c (>>1 MA/cm^2).
- Exceptions to the trend line were used as an opportunity to decipher the direction to take for microstructure and performance optimization.



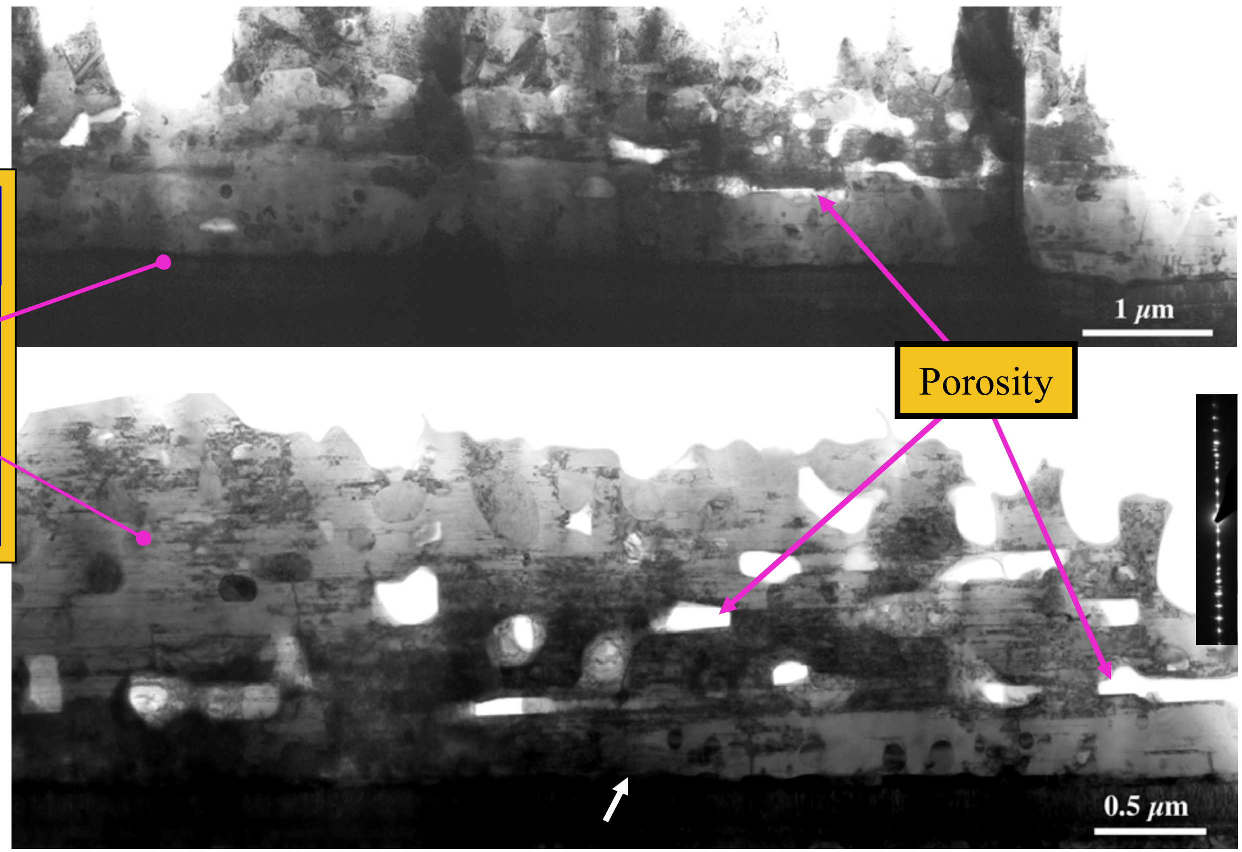
Exceptions to the J_c trend line show variants of the bimodal structure: no second phase layers and reduced out-of-plane tilt.

- It appears that porosity plays a role in the development of high J_c microstructures.

Example 1: Bimodal structure without second phase (S.P.)layers

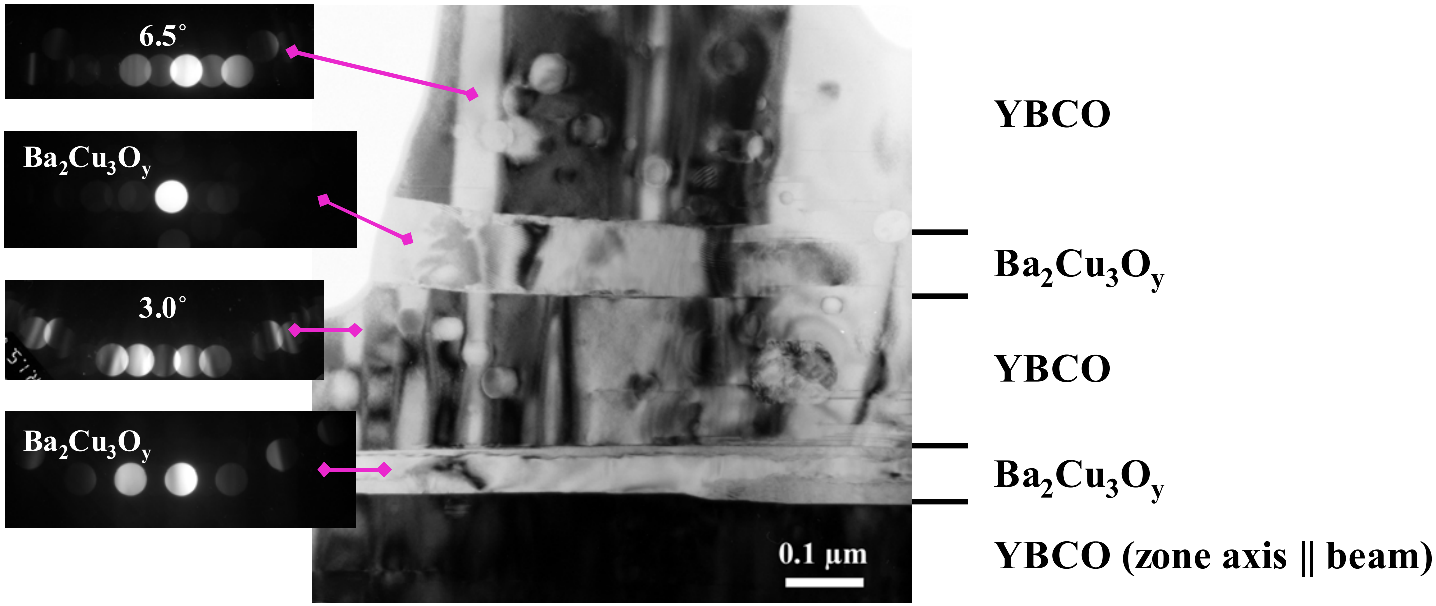
t (µm)	$\Delta\omega_{YBCO}$-ω_{YSZ}	J_c (A/cm^2)	S.P. Layers
1.4	-0.5Þ	1.69	No
1.4	+0.6Þ	1.05	Yes
1.8	+0.6Þ	0.9	No
2	+1.1Þ	0.4	Yes

Example 2: Partial bimodal structure without second phase layers



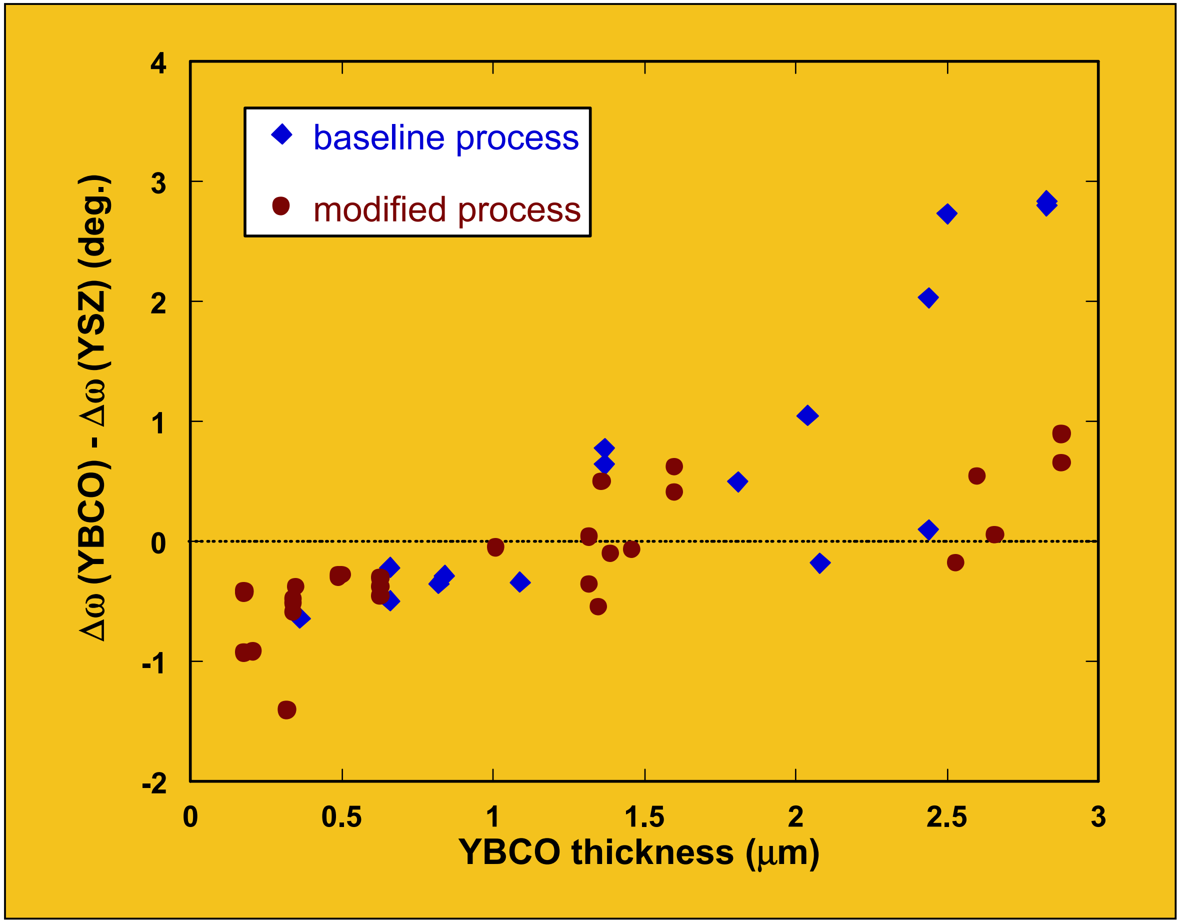
End of large grain with precipitates

Each second phase layer in a bimodal structure has the potential for YBCO alignment degradation.



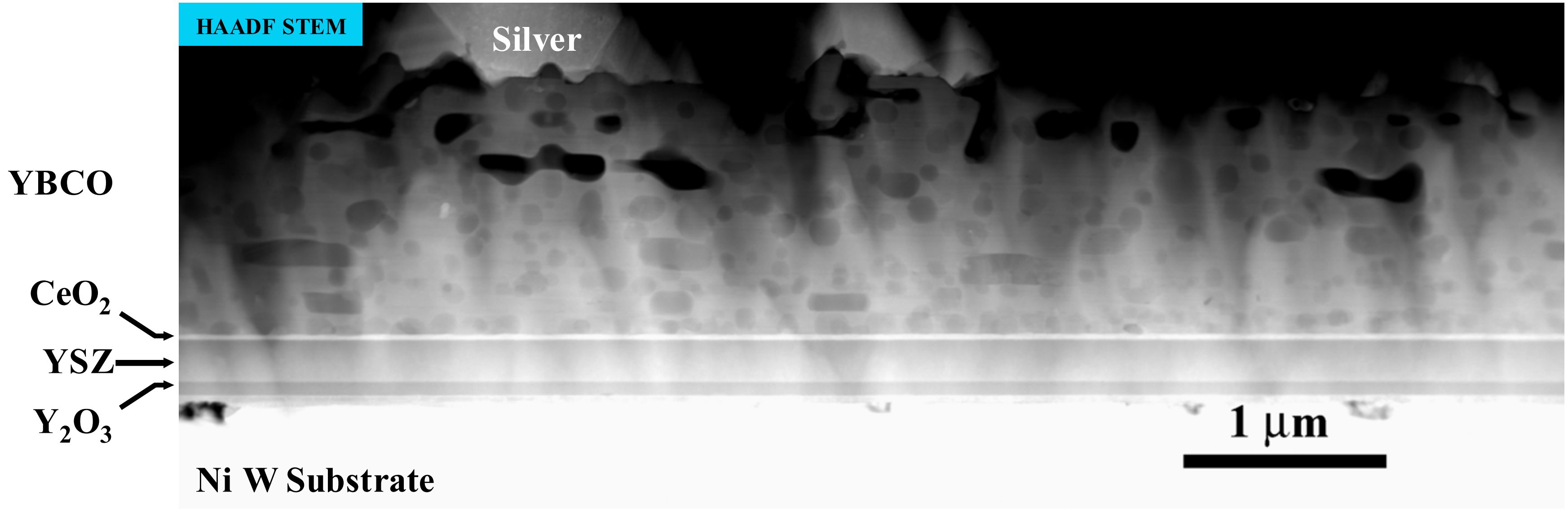
Modified processing has demonstrated a reduced out-of-plane alignment for *ex situ* YBCO films of thicknesses greater than 1 µm

- XRD data is consistent with the reduction or elimination of second phase layers in *ex situ* YBCO films made with the modified process.



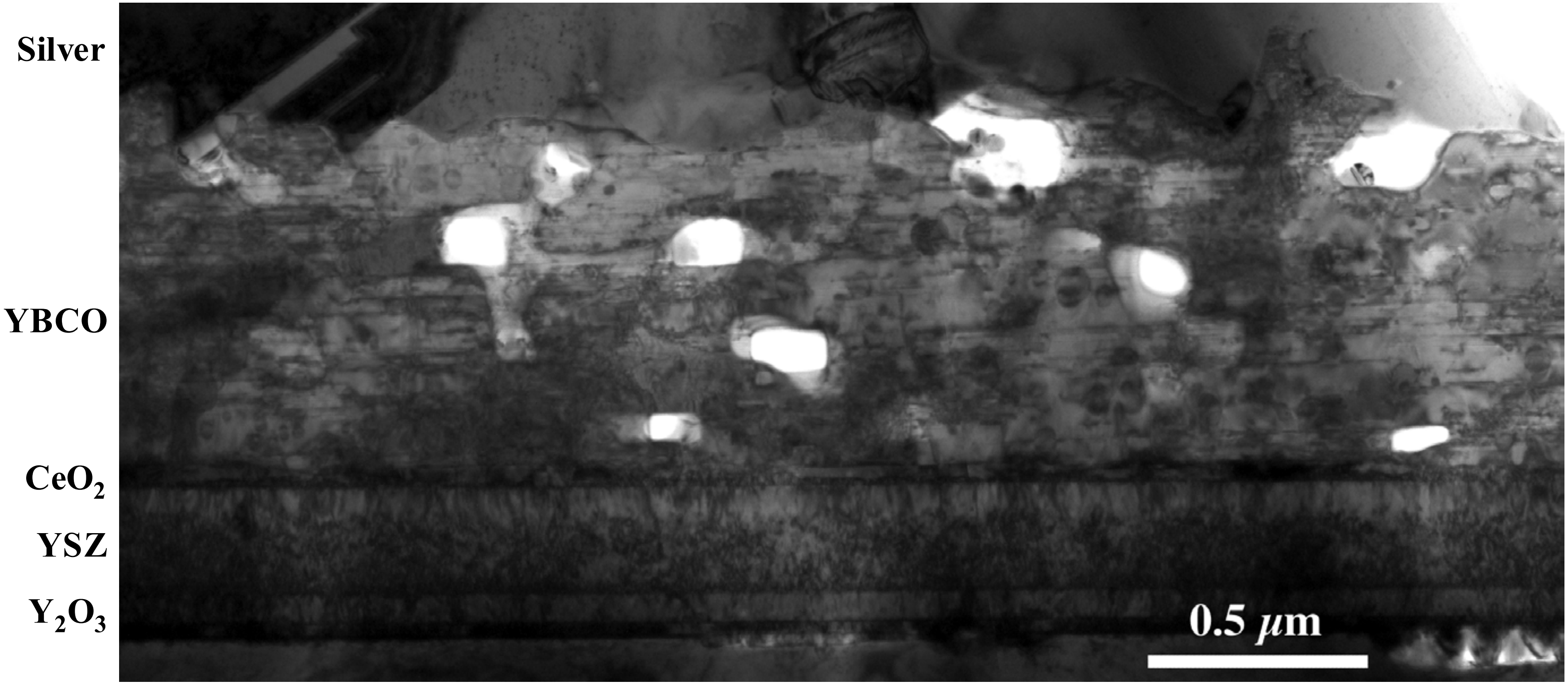
A fast modified process was developed in FY2004 to produce high-J_c, I_c films with a uniform, thru-thickness microstructure.

- Much higher performance levels **t = 1.25 µm, J_c = 2.7 MA/cm^2 I_c = 334 A/cm-w**
- New process appears to modify liquid phase generation.
  - No second phase layers
  - Porosity is present
  - Uniform distribution of planar defects and secondary phases thru thickness
- Minimized reactions with CeO_2 layer.
- AMSC RABiTS template.



High performance MOD BaF_2 YBCO *ex situ* films have a uniform, thru-thickness microstructure.

- Uniform distribution of secondary phases and planar defects.
- No second phase layers; porosity distributed thru thickness.
- 250 A/cm-w, t = 0.8 μm, J_c = 3.1 MA/cm^2



Summary

- Developed an understanding of the causes and effects of the bimodal microstructure.
  - Second phase layers cause misalignments and reduce J_c.
  - Variants of bimodal structure without S.P. layers allow for higher J_c values.
  - Development of a through-thickness uniform microstructure with even higher J_c's.
- Several unique characteristics of *ex situ* grown YBCO films.
  - Laminar growth
  - Grain boundary meandering / Grain boundary overgrowth
- Currently believe that some porosity in the *ex situ* YBCO films is needed for material transport within the film during conversion. Fully dense structures may trap liquid phases leading to second phase layers.
- Samples processed by the new "fast-modified" process show uniform thru-thickness microstructures.
  - Uniform distribution of planar defects and second phases.
  - Reduced interfacial reactions with CeO_2.
  - Microstructures of high-J_c MOD and PVD-BaF_2 films very similar.

Outline

- Liquid phase formation, laminar growth, and microstructural development of high-J_c ex-situ films — Terry Holesinger

- **Through-thickness grain boundary networks: Observation of complex GB structures in *ex situ* films — Matt Feldmann**

- Processing for high I_c *ex situ* YBCO coated conductors (PVD BaF_2 process) — Ron Feenstra

Through-thickness grain boundary networks

Observation of complex GB structures in *ex situ* films

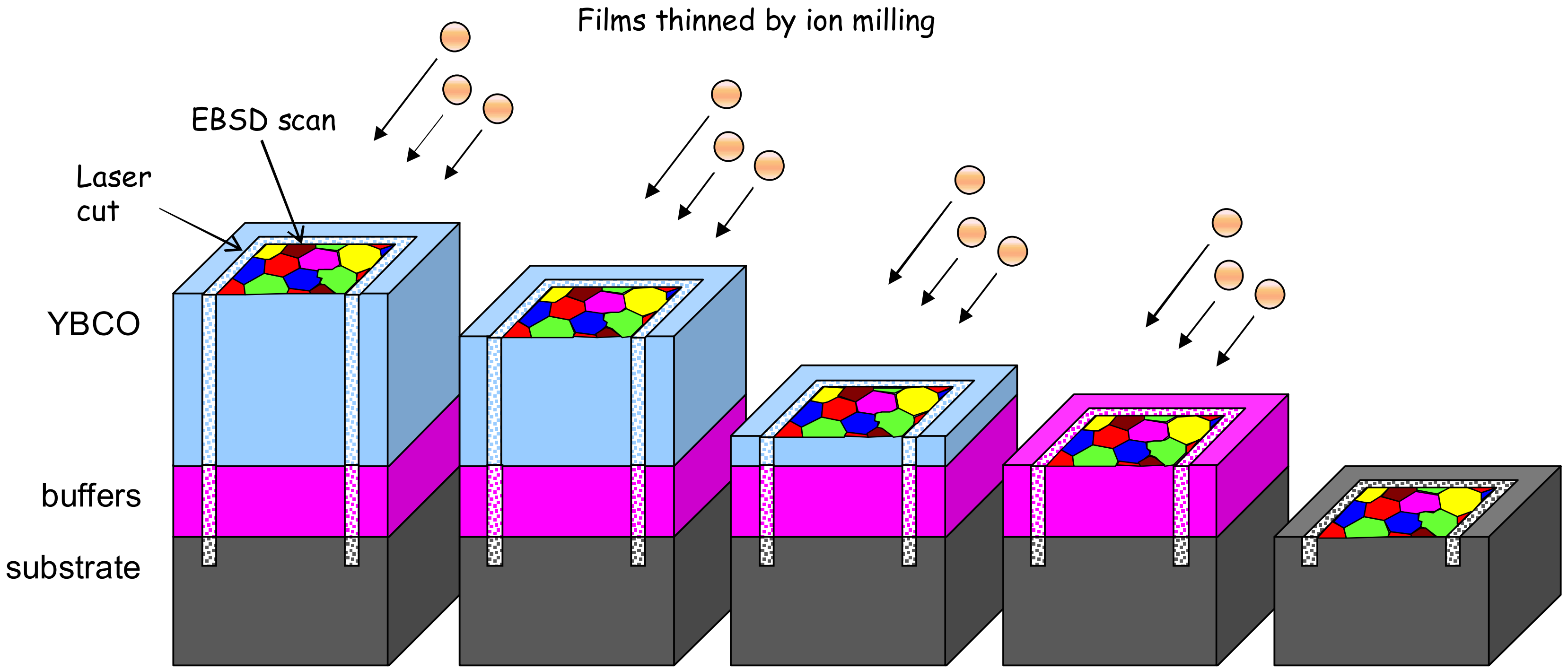
- Substrate grain boundary overgrowth
  - Result of liquid mediated growth mode
- Complex GB architecture in coated conductors
  - GB “meandering”
- Preliminary YBCO bi-crystal results
  - Investigate correlation between J_c and GB architecture

YBCO thickness	template	BaF_2 process	I_c (A/cm)	J_c(MA/cm^2)
0.5 μm	RABiTS	PVD	105	2.1
0.9 μm	RABiTS	MOD	250	3.1
1.0 μm	RABiTS	PVD	240	2.4
2.5 μm	RABiTS	PVD	150	0.6
2.9 μm	IBAD-YSZ	PVD	280	0.9

EBSD scans through thickness provide 3D view of YBCO grain structure

EBSD = Electron Back-Scatter Diffraction (a.k.a. EBKP, OIM)

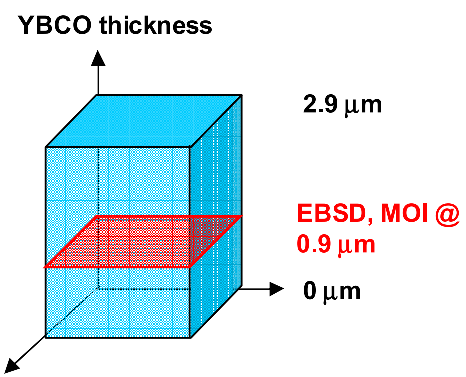
- High quality Kikuchi patterns have been obtained from ion milled surfaces
- Laser cuts provide registration through thickness



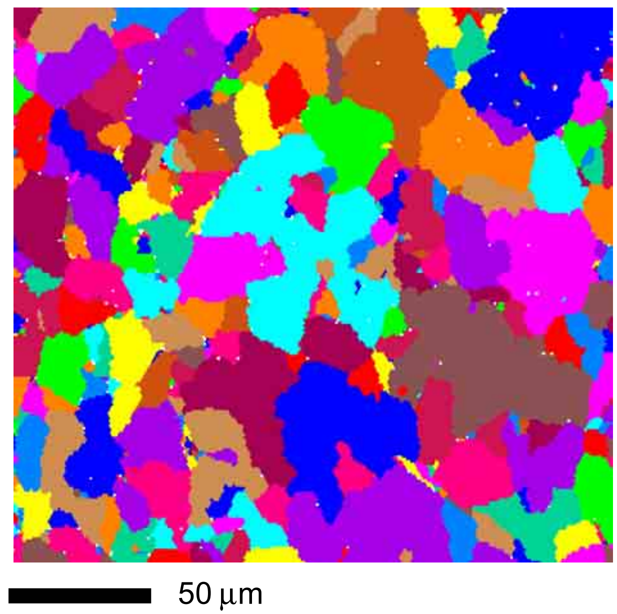
Liquid mediated YBCO growth mode leads to substrate grain boundary overgrowth on IBAD-YSZ

- YBCO grain size ~ 30-50 μm; IBAD-YSZ grain size ~ 0.1 μm
- YBCO grains overgrow many substrate grains and grain boundaries

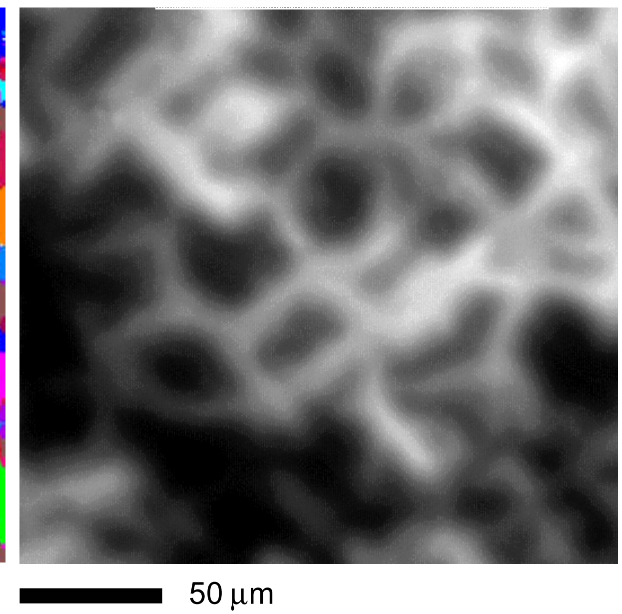
$d = 2.9\ \mu m$
$J_c = 0.9\ MA/cm^2$
$I_c = 280\ A/cm$



EBSD 1° Unique Grain map



Magneto-optical image



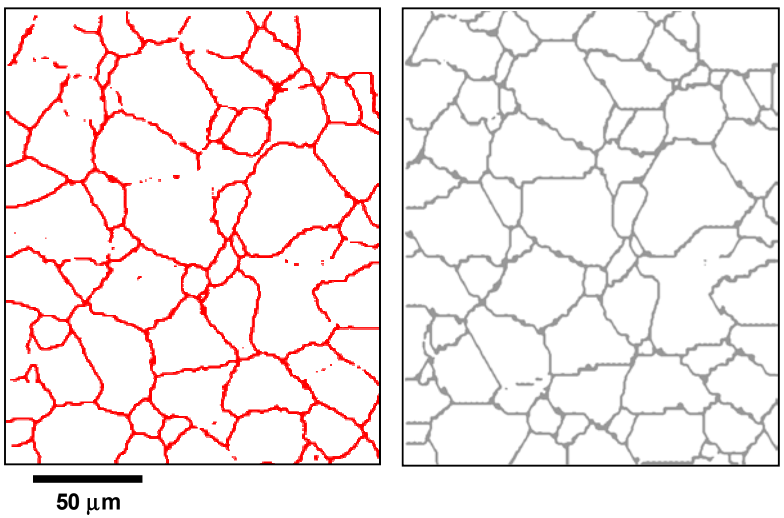
(different spatial locations)

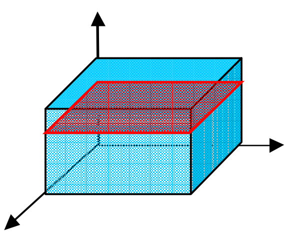
Liquid mediated growth in thick (≥1 μm) YBCO films also leads to substrate grain boundary overgrowth on RABiTS

d = 0.5 μm
J_c = 2.1 MA/cm^2

YBCO
ALL GBs ≥2°

Underlying NiW
ALL GBs ≥2°

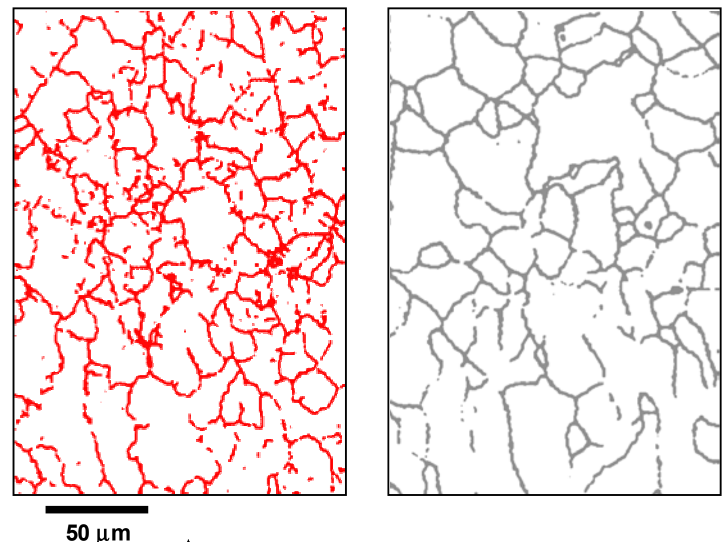


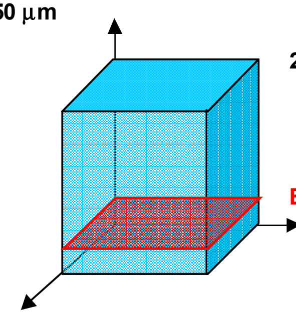


d = 2.5 μm
J_c = 0.6 MA/cm^2

YBCO
ALL GBs ≥2°

Underlying NiW
ALL GBs ≥2°



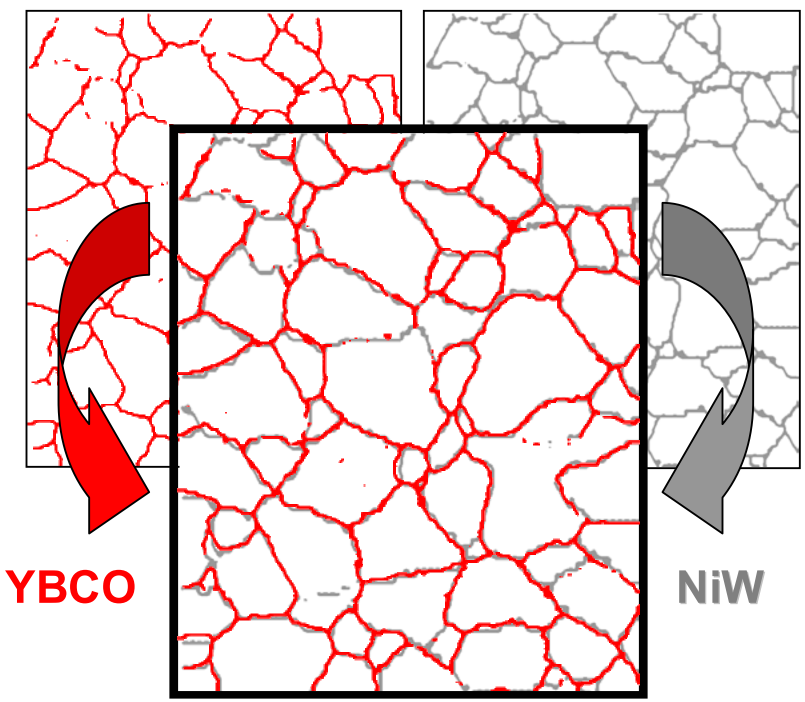


Liquid mediated growth in thick (≥1 μm) YBCO films also leads to substrate grain boundary overgrowth on RABiTS

d = 0.5 μm

GBs line up!

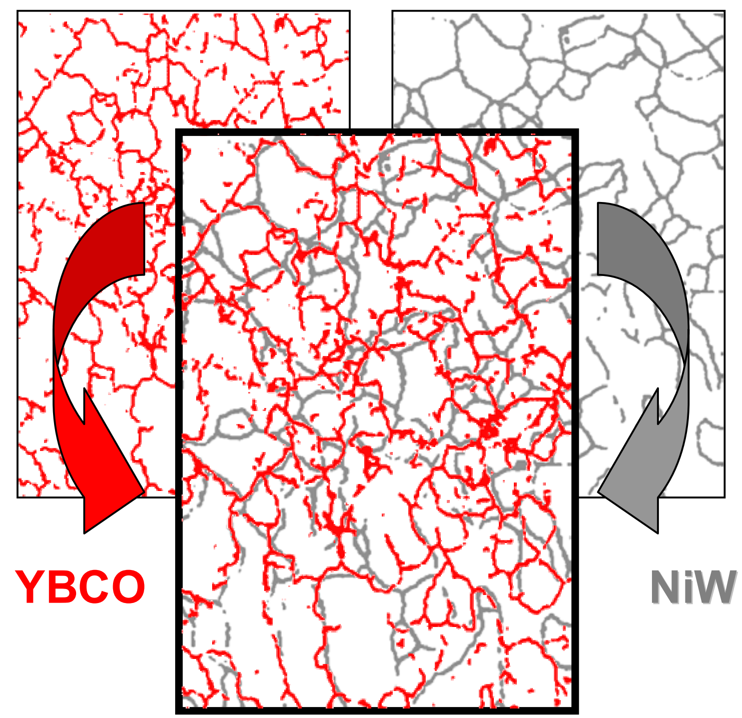
(typical 'thin-film' behavior)



d = 2.5 μm

GBs don't line up!

(substrate GB overgrowth)

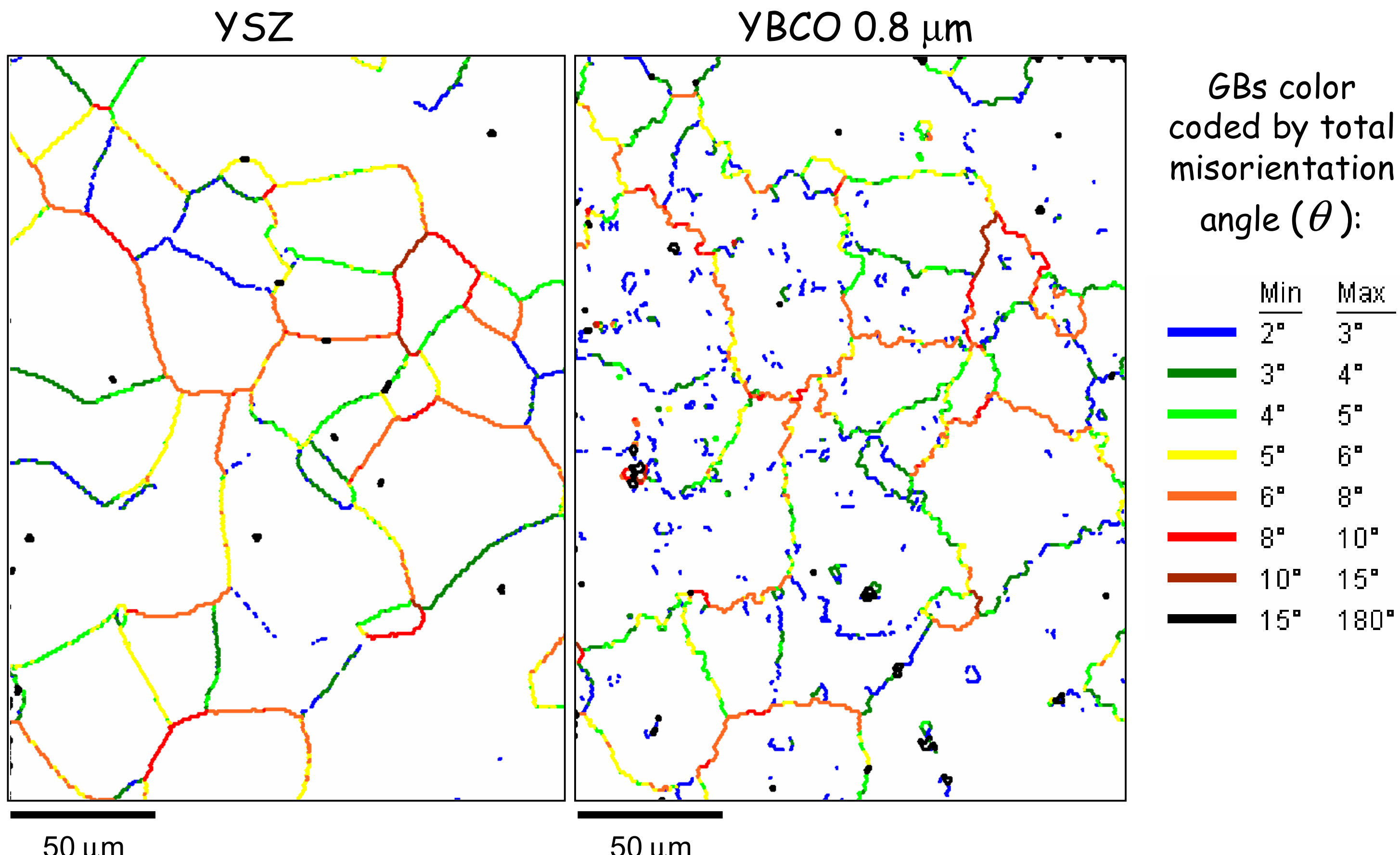


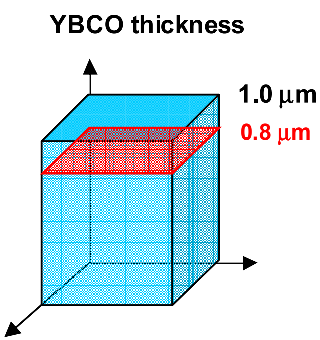
*D.M. Feldmann et al, APL **77** 2906 (2000)*

1.0 μm thick "fast process" YBCO film shows intermediate role of liquids — GB meandering

- YBCO: substrate grain structure is recognizable, but GBs "meander"

J_c = 2.4 MA/cm^2
I_c = 240 A/cm
RABiTS

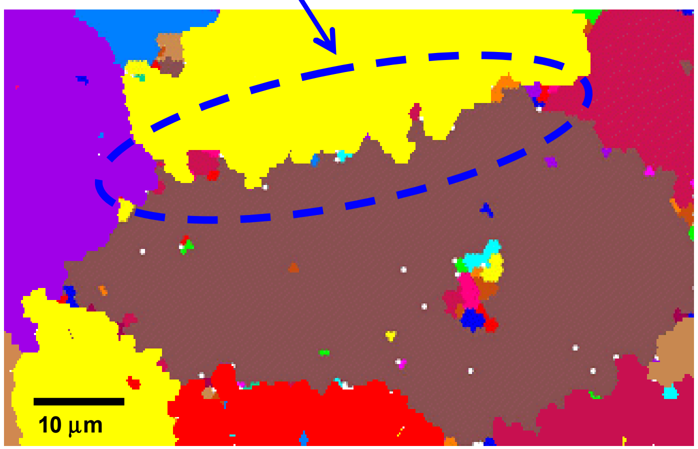




GB meandering is reproducible under different scan conditions

Very similar meander observed for both scan conditions

1.0 μm step size
Beam Energy = 30 kV



0.6 μm step size
Beam Energy = 20 kV

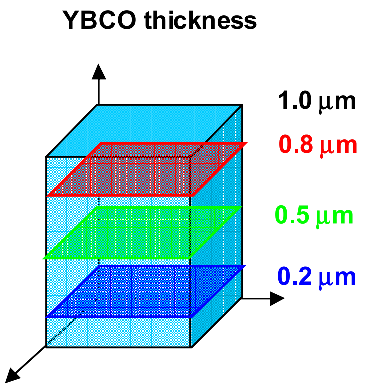
(~70% smaller YBCO volume sampled at each point*)

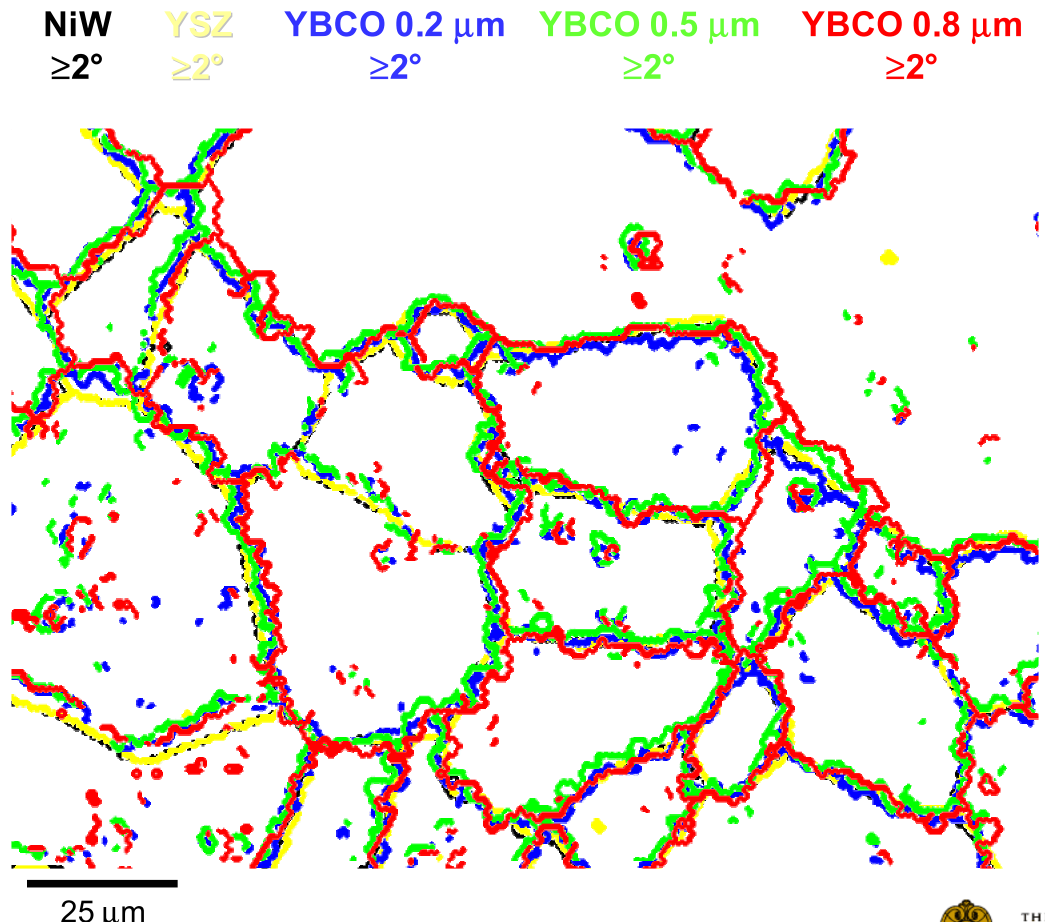
A. Goyal et al, Micron **30 463 (1999)*

1.0 μm thick "fast process" YBCO film shows significant plan-view and through-thickness GB meandering

➢ θ remains constant through thickness – Meandering increases GB area

J_c = 2.4 MA/cm^2
I_c = 240 A/cm
RABiTS





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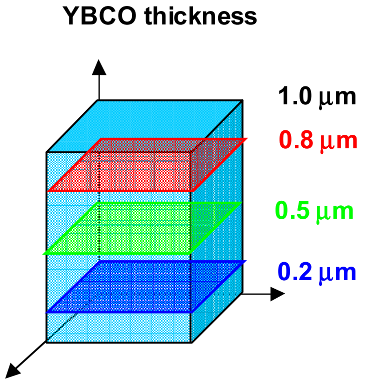
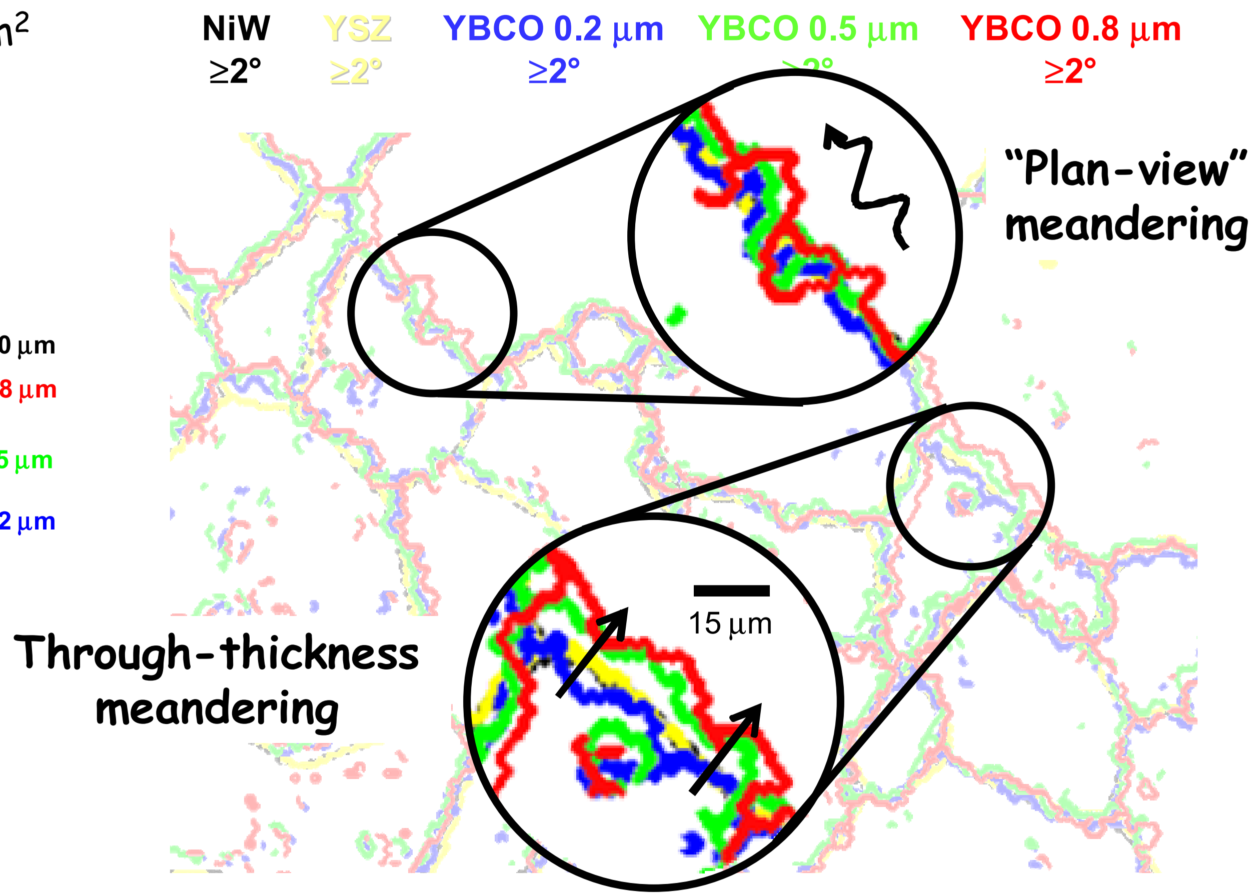


YBCO GB moved ~15 μm through a thickness of only 0.6 μm (from 0.2 to 0.8 μm)

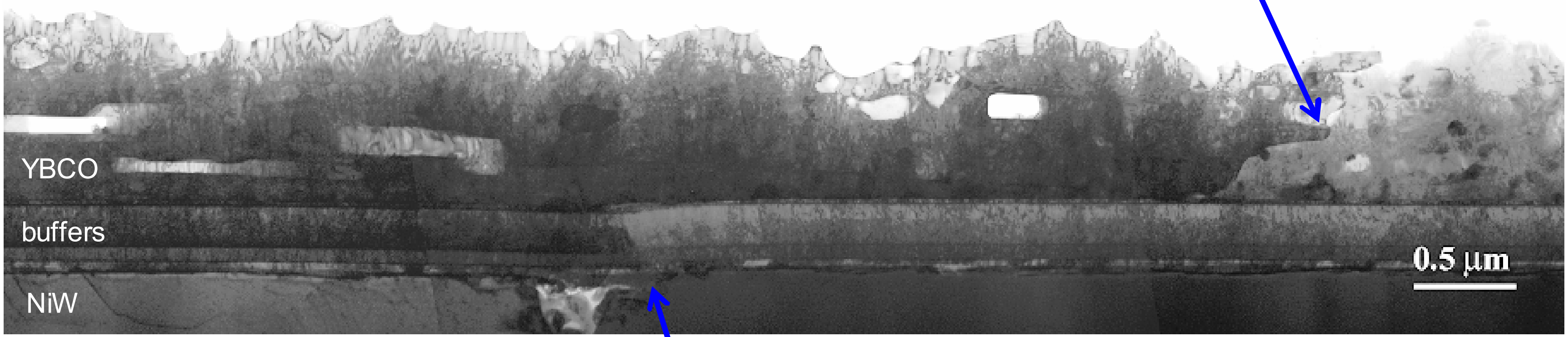


Substrate GB overgrowth and through-thickness meandering also observed with x-sec TEM

d = 1.25 µm

$J_c(0,77K) = 2.7\ MA/cm^2$

YBCO boundary



T.G. Holesinger (LANL)

substrate boundary

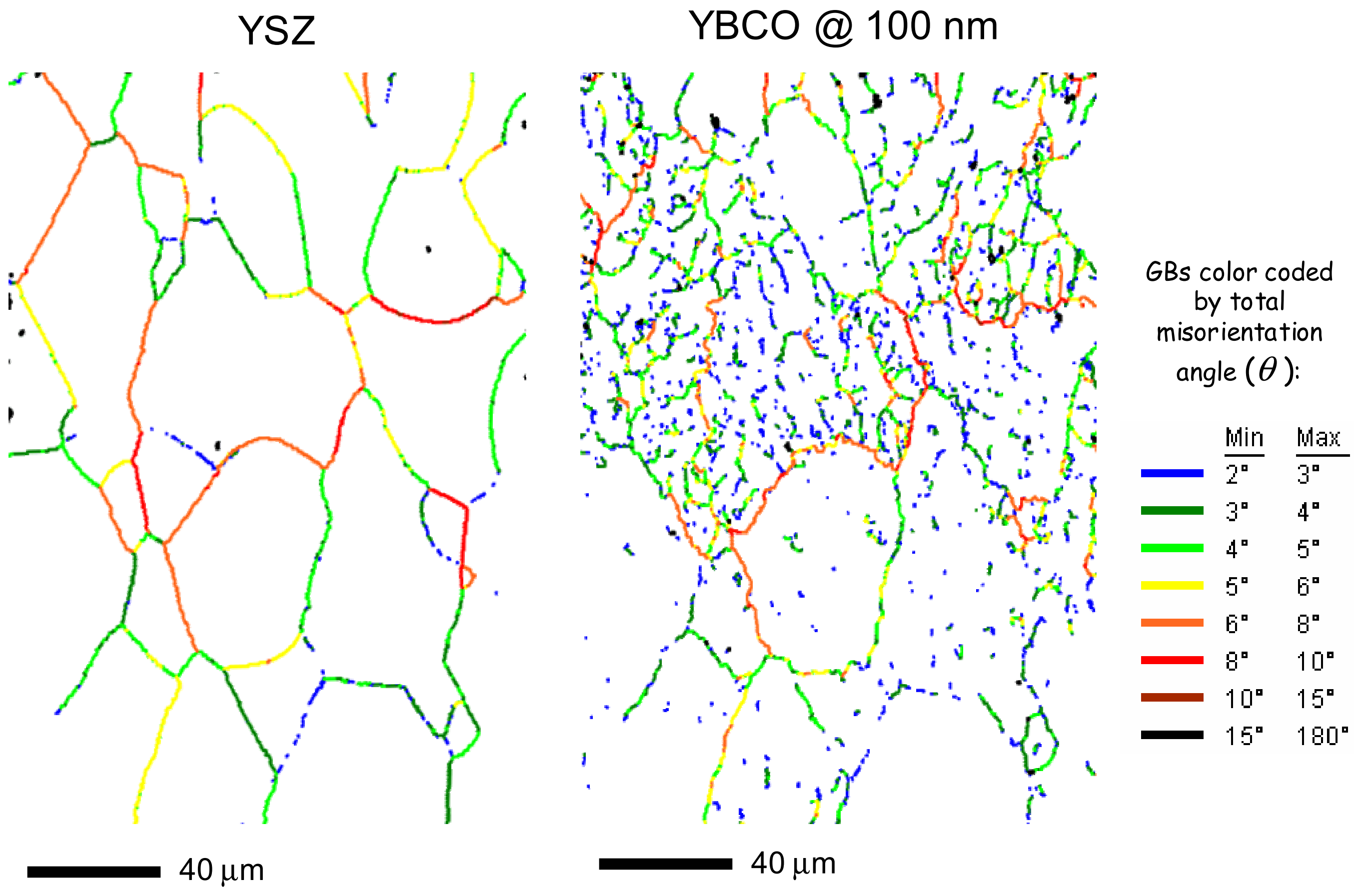
MOD BaF_2 process films on RABiTS exhibit GB meandering and a YBCO "sub-grain" structure

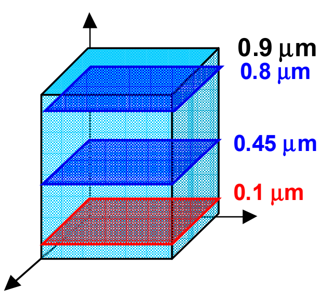
- Both plan-view and through thickness meandering observed, but more pronounced in PVD films

- Additional YBCO sub-grain structure found

American Superconductor

J_c = 3.1 MA/cm^2
I_c = 250 A/cm
RABiTS





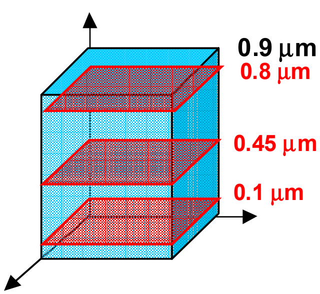
EBSD (not shown) also shows through-thickness GB meandering

MOD BaF_2 process films on RABiTS exhibit GB meandering and a YBCO "sub-grain" structure

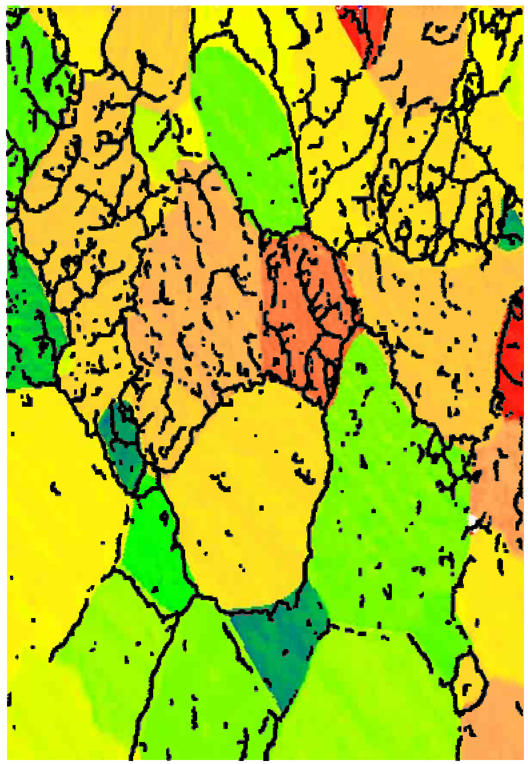
- *Sub-grain structure appears above substrate grains with greater out of plane tilt*

American Superconductor

J_c = 3.1 MA/cm^2
I_c = 250 A/cm
RABiTS

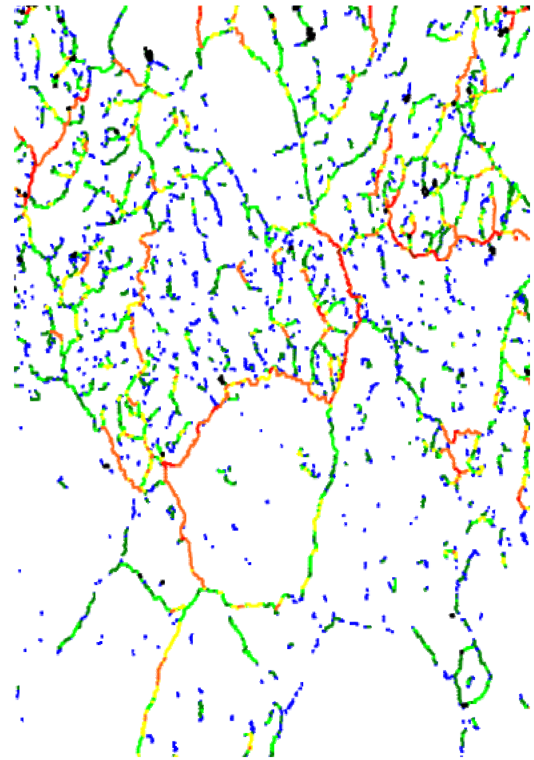


YSZ *out of plane orientation*



40 µm

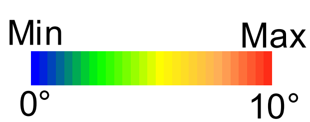
YBCO @ 100 nm



40 µm

GBs color coded by total misorientation angle (θ):

Min	Max
2°	3°
3°	4°
4°	5°
5°	6°
6°	8°
8°	10°
10°	15°
15°	180°

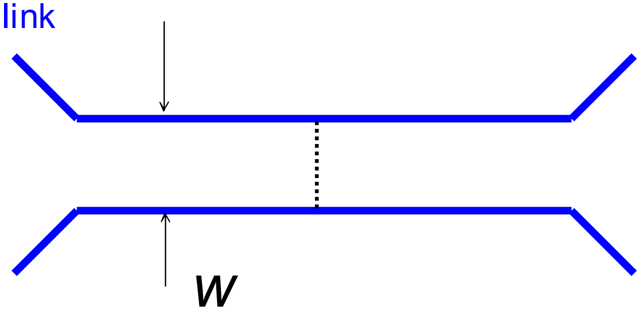


Angle between sample normal and nearest crystal axis

Does an increased GB area result in a higher I_c?

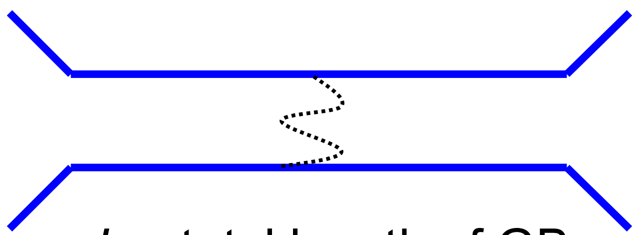
YBCO link

"straight" GB



$$I_c = J_c(GB) \times w \times d$$

"meandering" GB



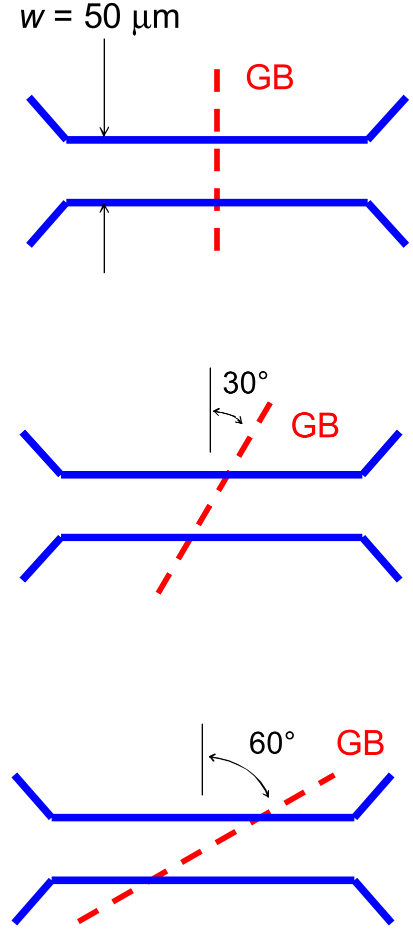
L = total length of GB

$L > w$

$$I_c \sim J_c(GB) \times L \times d\ ??$$

Bi-crystal experiment motivated by observation of GB meandering in CCs

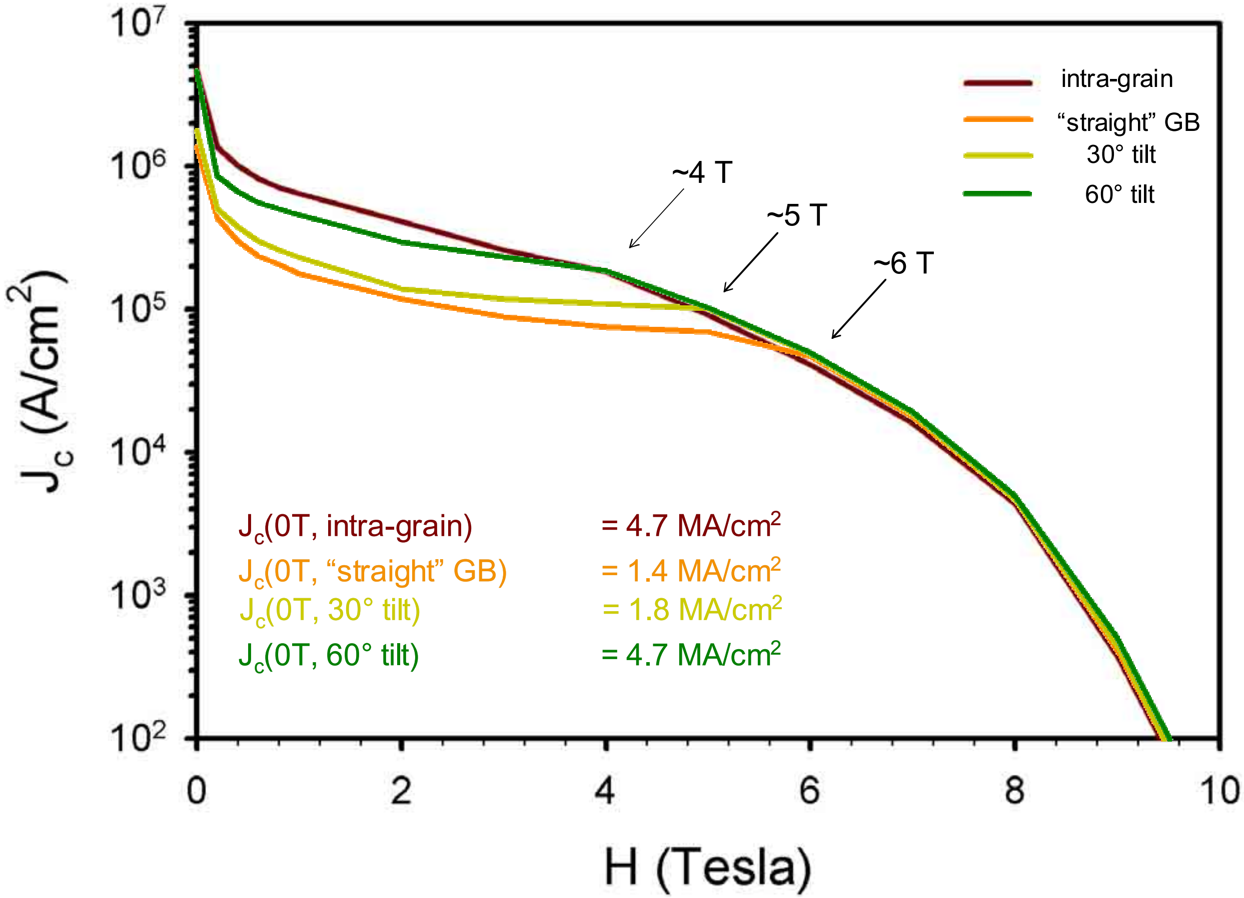
- ❖ YBCO films grown by PLD (d = 0.18 μm)
- ❖ 5° STO bicrystal substrates (no buffers)
- ❖ Width of links held fixed at 50 μm

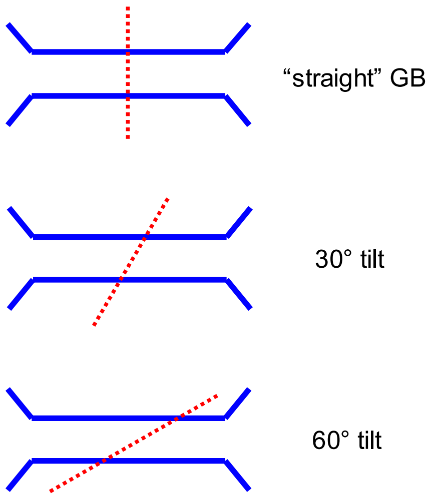


	GB length
"straight" GB	*w*
30° tilt	1.15 *w*
60° tilt	2 *w*

Oblique GBs result in a higher link J_c

➢ Increasing the GB area appears to improve the transparency of the GB to transport current





Summary

- Liquid mediated growth mode allows YBCO to overgrow substrate GBs

- The different roles of liquids in *ex situ* films produce different grain and GB geometries

  d = 0.5 μm — "straight" GBs – *reduced role of liquids*
  - YBCO GBs overlap substrate GBs

  d = 1.0 μm — "meandering" GBs – *intermediate role of liquids*
  - YBCO GBs meander along substrate GBs

  d = 2.5 μm — large substrate GB overgrowth – *excessive liquid growth*
  - Almost complete disconnect between YBCO and substrate GBs

- Complex GB architecture observed in CCs
  - "plan-view" and through-thickness GB meandering discovered
  - Bi-crystal experiment suggests a relationship between GB area and overall J_c
  - θ alone is insufficient to describe the transport properties of GBs in CCs

Outline

- Liquid phase formation, laminar growth, and microstructural development of high-J_c ex-situ films — Terry Holesinger

- Through-thickness grain boundary networks: Observation of complex GB structures in *ex situ* films — Matt Feldmann

- **Processing for high I_c *ex situ* YBCO coated conductors (PVD BaF_2 process)** — **Ron Feenstra**

Processing for high I_c ex situ YBCO coated conductors ($PVD-BaF_2$ process)

FY2004 milestones

- **obtain 10 Å/s growth rate with $PVD-BaF_2$ precursors**
  - equivalent duration: 17 min / μm
  - previously: 2-3 h / μm ("standard" process)
- **increase I_c on CC substrates to values > 400 A/cm (77 K)**
  - previous best values:

    235 A/cm 2.5 μm YBCO on Ni-W RABiTS (ORNL)

    280 A/cm 2.9 μm YBCO on IBAD-YSZ (LANL)

➢ Added task related to participation in the CC-WDG (since 12/2003):
"study origin of and improve flux pinning in $PVD-BaF_2$ conductors"

Strategies to increase I_c

FY2004

- "lean and mean"

  increase J_c for intermediate 1-1.5 μm thickness range

  \+ AMSC has realized large gains in I_c of 1 μm YBCO by process improvements

- "brute force"

  produce thick YBCO coatings: d > 2 μm

  \+ unique opportunities for PVD-BaF_2 process

  \+ irreversible strain limit ε_{irr} > 0.4% in 2.75 μm YBCO on Ni-5%W RABiTS (NIST-Boulder, this Review)

  – limited overlap with MOD

- "smart"

  study origin of thickness dependence of J_c

  \+ focus of work in FY2003

"Killing two birds with one stone"

Central to the progress in FY2004 was the development of a fast process yielding higher I_c than "standard" (slow) processing

- development of the fast process
- thickness dependent trends in I_c
- flux pinning
- thickness dependence of J_c
  - very thin films on RABiTS (d_{min} = 15 YBCO unit cells)

➢ Summary of results (scoring criterion)
➢ Performance and plans (scoring criterion)
➢ Technology integration (scoring criterion)

A fast conversion process was developed for PVD-BaF_2 precursors

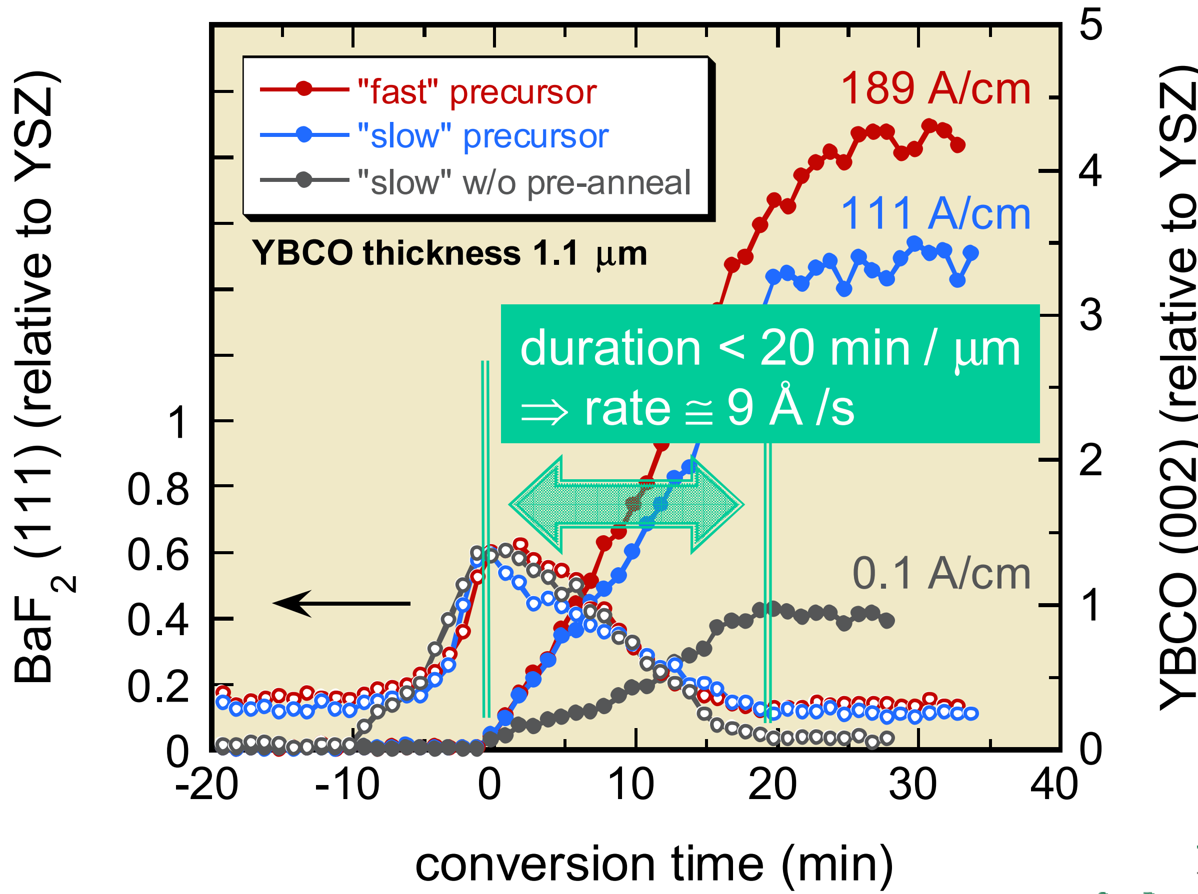
- New processing scheme ties together precursor preparation history and the ex situ conversion
  - tighter control of precursor deposition conditions
  - insertion of intermediate, low-T anneal
  - “aggressive” conversion conditions (gas flow, T, p(H_2O))

- Development builds on previous work:
  - review of available thick film database
  - observations during latter part of 3M-ORNL CRADA (until Fall 2002)
  - FY2003 development of “modified” process for thick YBCO
  - preliminary results (reported at 2003 Peer Review)

    J_c = 1.0 MA/cm^2 (77 K) in 0.8 μm YBCO converted at 6 Å/s

PVD-BaF_2 precursors capable of fast conversion were identified

- YBCO growth rates measured by in situ XRD (vacuum conversion)
  total pressure: 500 mTorr, YBCO area: 3 cm^2



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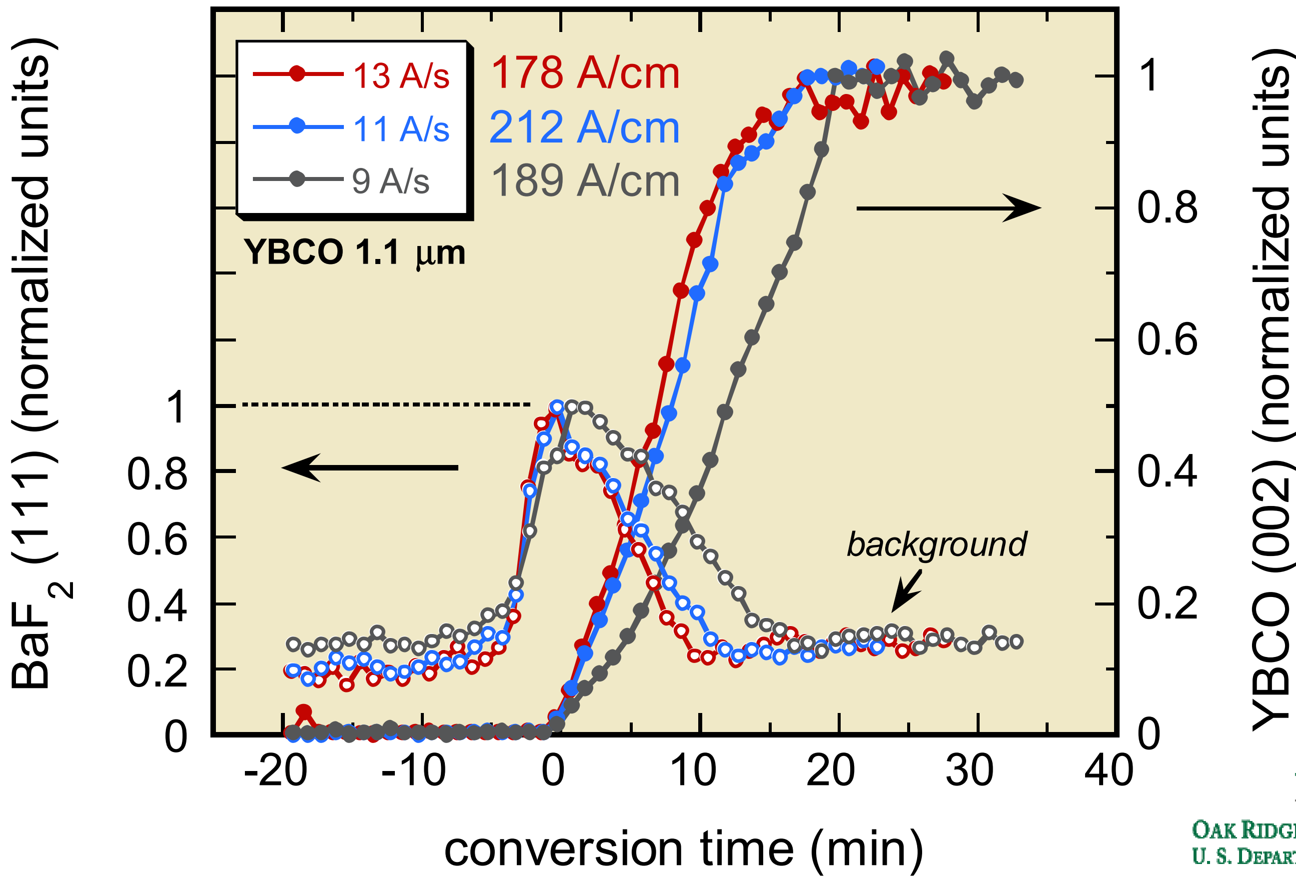
Fast conversion process results in I_c > 200 A/cm at rates >10 Å/s (duration < 17 min / μm)

✓ FY2004 milestone of 10 Å/s has been met

- Fast conversion was also obtained in standard conversion system with flowing gas at 1 atm pressure (YBCO area: 0.3 cm^2)



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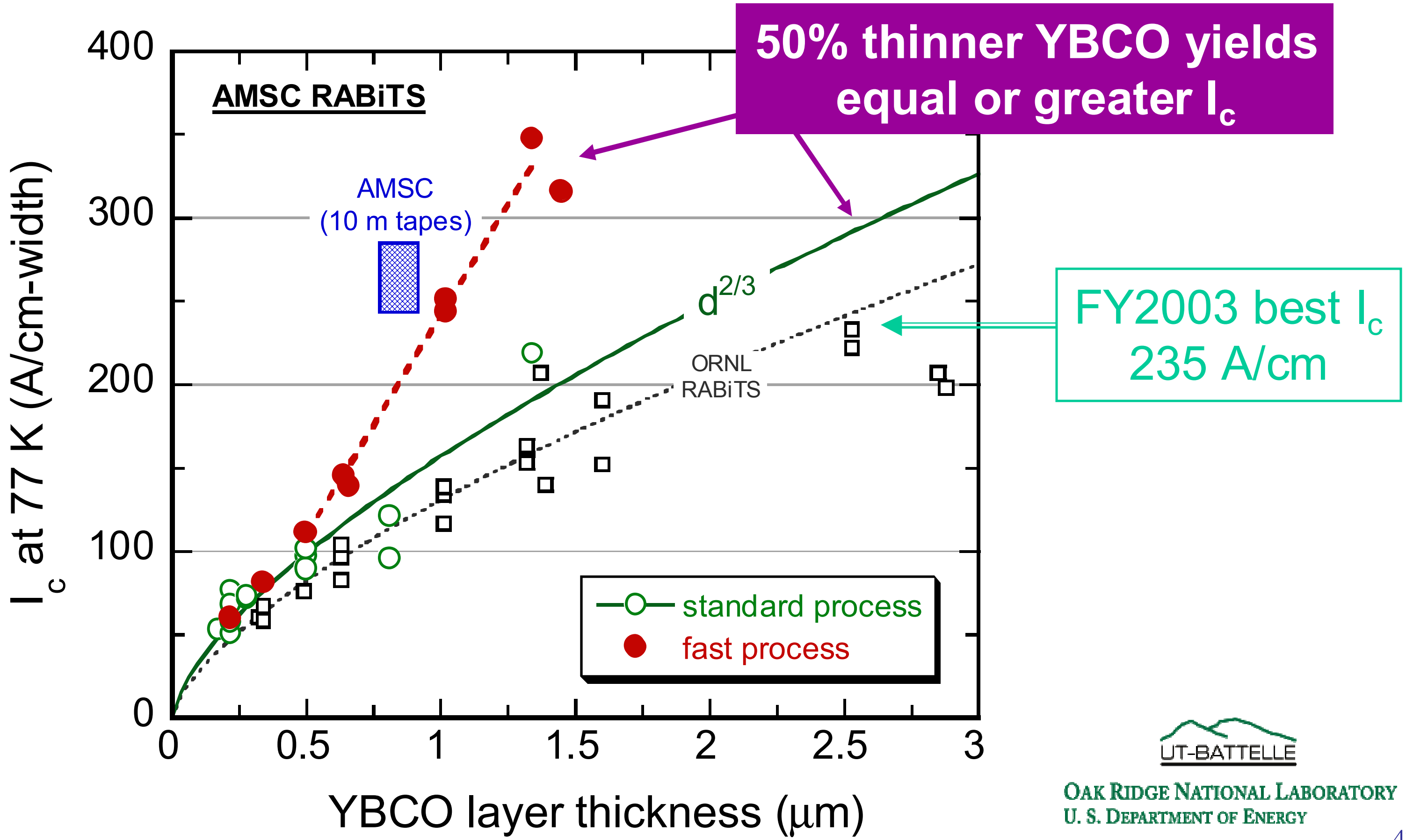
I_c of fast processed films increases linearly with the YBCO thickness (0.5-1.3 μm)

- films were grown on AMSC RABiTS (~20% higher I_c than ORNL RABiTS)
- "standard" process yields reducing I_c increments with d: $I_c \propto d^{2/3}$ (or $d^{1/2}$)
- I_c determined from systematic extrapolation of $H \leq 1$ T data



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Through-thickness imaging of fast-processed film shows a meandered GB structure

YBCO grain size is similar to substrate, constant through thickness
$\Rightarrow$ no bimodal structure (TEM)

original thickness: 1.35 μm
process: 29 min / μm
I_c = 347 A/cm
J_c= 2.6 MA/cm^2

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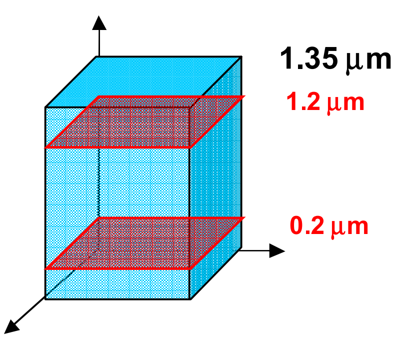
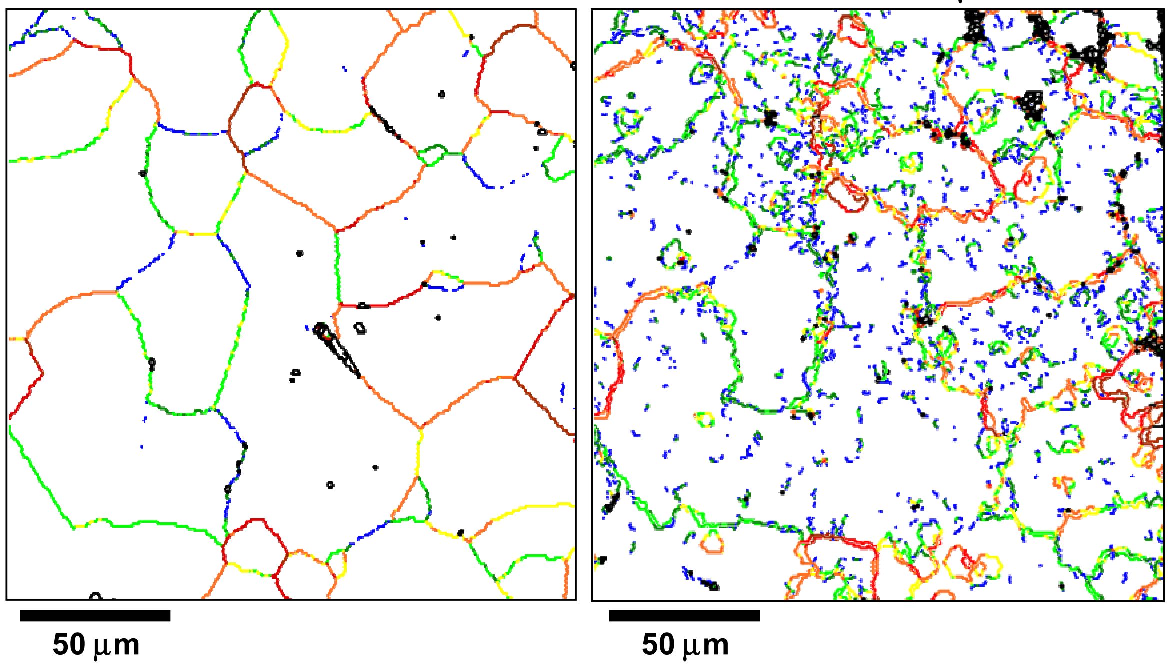


YSZ

+ 1.2 μm
YBCO 0.2 μm



GBs color coded by total misorientation angle (θ):

blue	2°	3°	orange	6°	8°
dark green	3°	4°	red	8°	10°
green	4°	5°	brown	10°	15°
yellow	5°	6°	black	15°	180°

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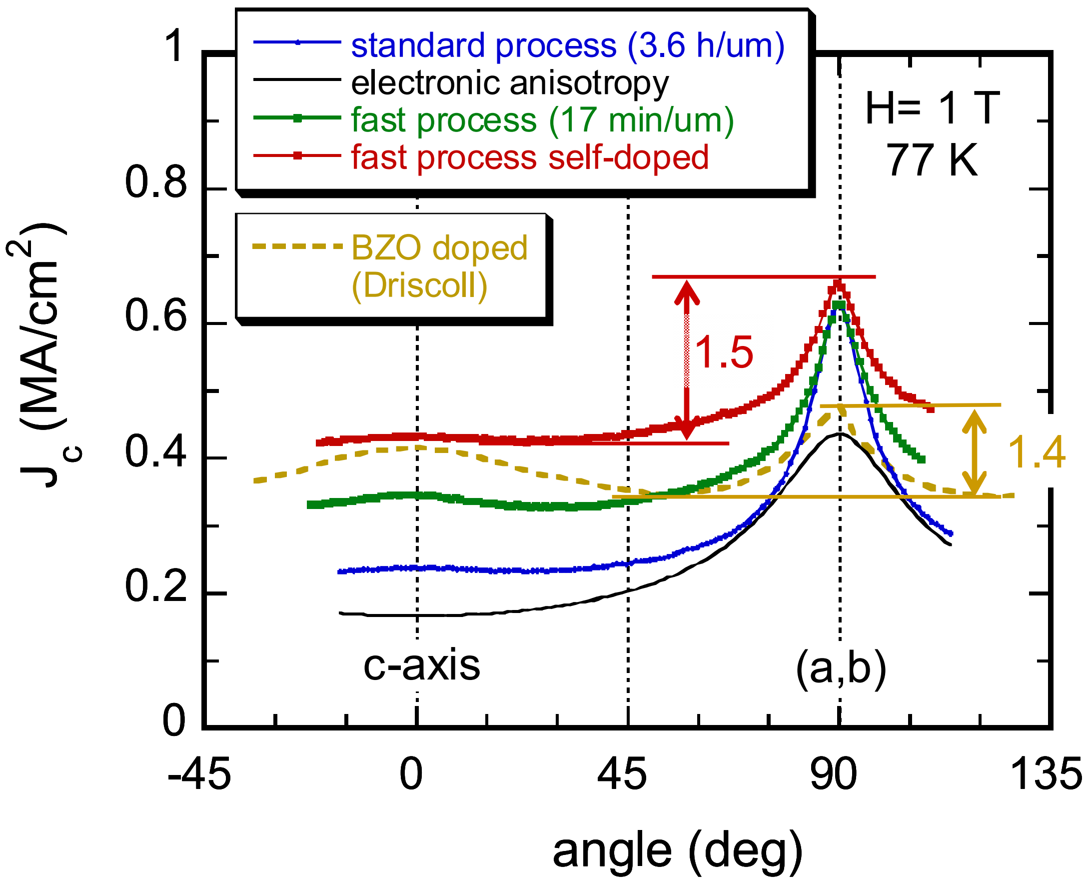
Fast-processed films exhibit strong flux pinning and reduced field-angle anisotropy J_c^{max} / J_c^{min}

- pinning is enhanced in orientations away from (a,b)—NO peak along c
- self-doping (off-stoichiometric precursors) further enhances J_c, pinning
- pinning strengths comparable to BZO-doping were obtained



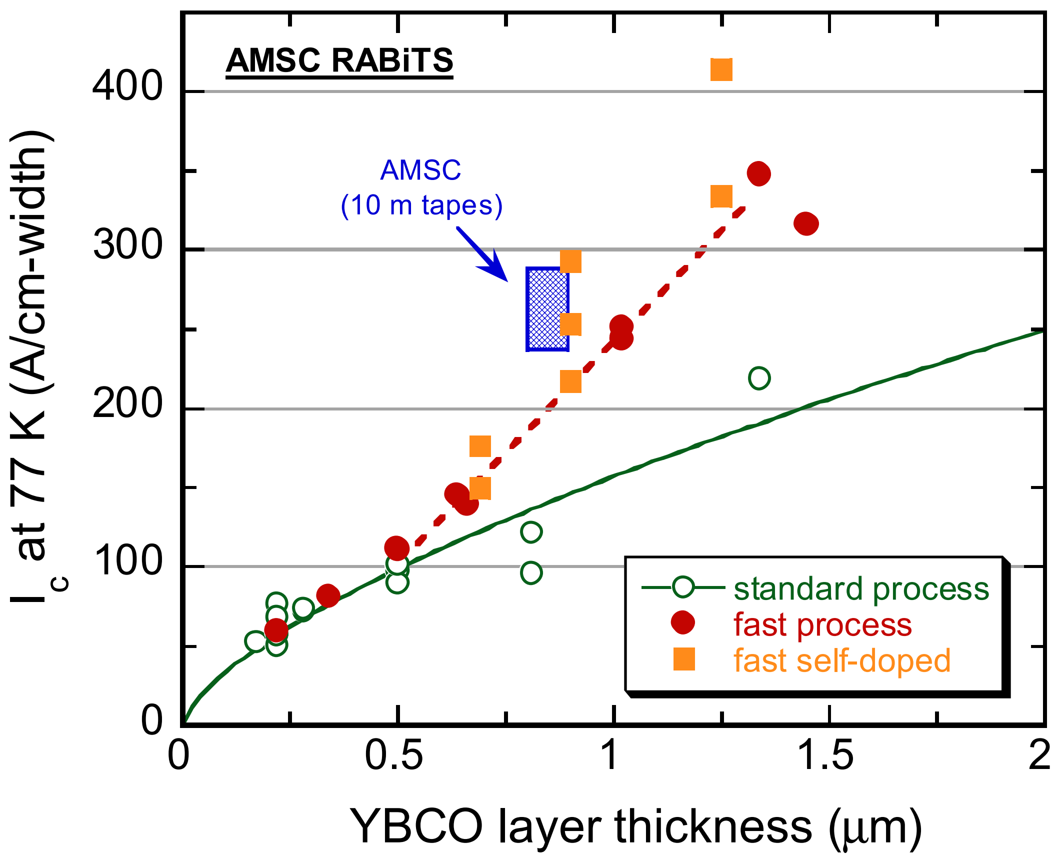
YBCO: 0.65-0.75 μm

sample	$J_c(0)$ (MA/cm^2)	ratio
standard	1.6	2.6
fast	2.3	1.9
fast-doped	2.5	1.5
BZO (LANL)	2.0	1.4
electronic (γ = 5)		2.6

J_c^{max} / J_c^{min}

Further I_c increases resulted from self-doped (off-stoichiometric) precursors

- flux pinning study: higher J_c (H||c) from doping-induced defects
- thickness-dependent study: same I_c reached for thinner YBCO



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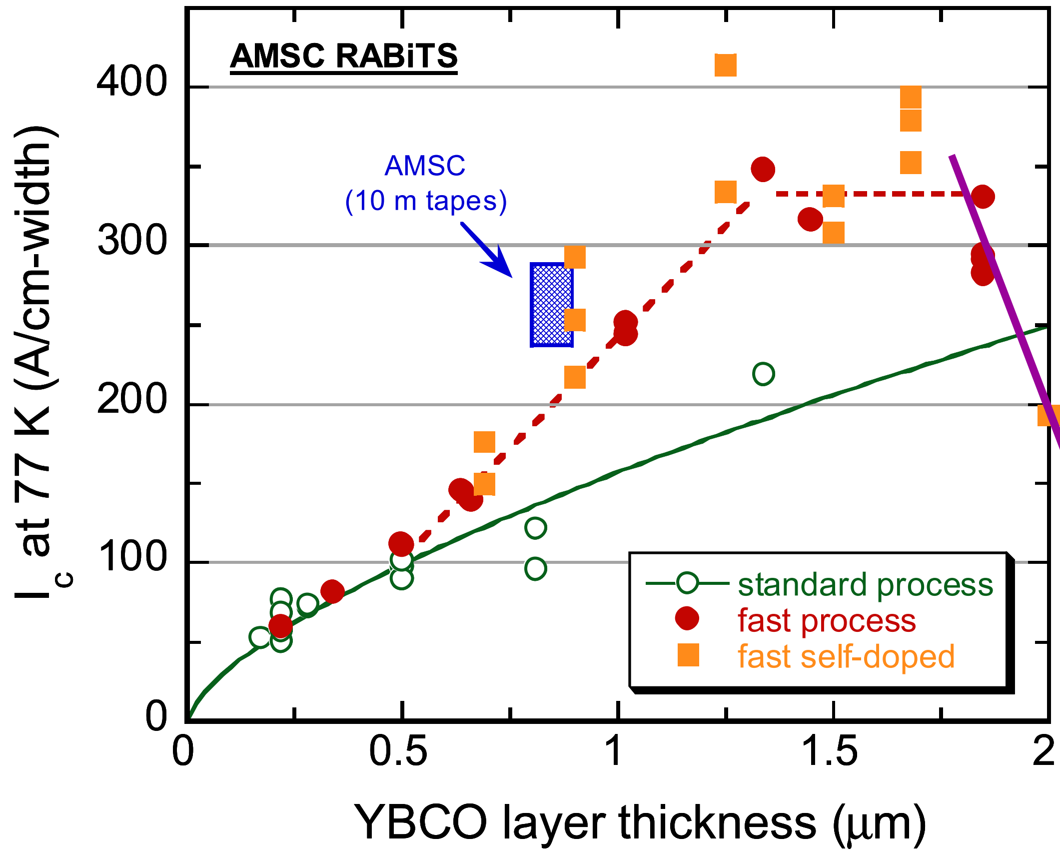
Linear relation between I_c and YBCO thickness ceases to hold for d > 1.3 μm

- higher I_c is obtained for self-doped YBCO also for d > 1.3 μm
- I_c decreases to values less than I_c of standard process for d > 2 um
- ➢ new processing ideas are needed for fast conversion of thick precursors



I_c decreases
not optimized

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Through-thickness imaging of the GB network reveals probable cause of the I_c-d stagnation

original YBCO thickness: 1.85 μm

process duration: 29 min / μm

"undoped"

I_c = 330 A/cm

J_c= 1.8 MA/cm²

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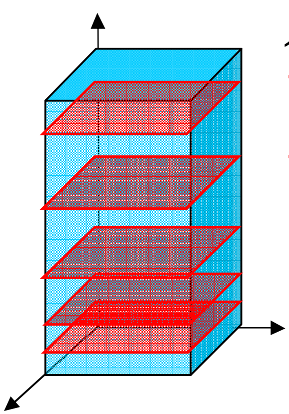

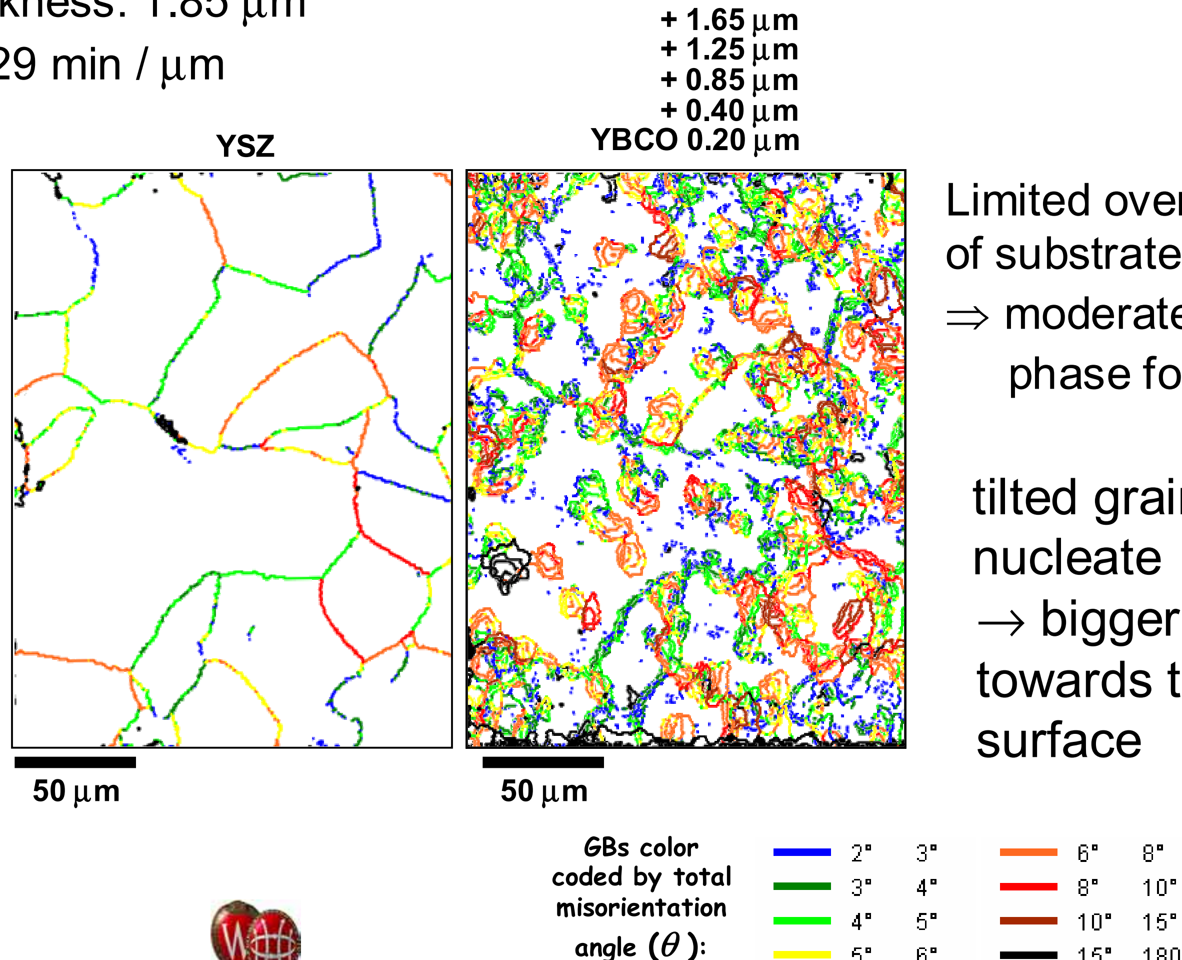

Limited overgrowth of substrate GBs
⇒ moderate liquid-phase formation

tilted grains nucleate
→ bigger towards the surface

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Summary of I_c results

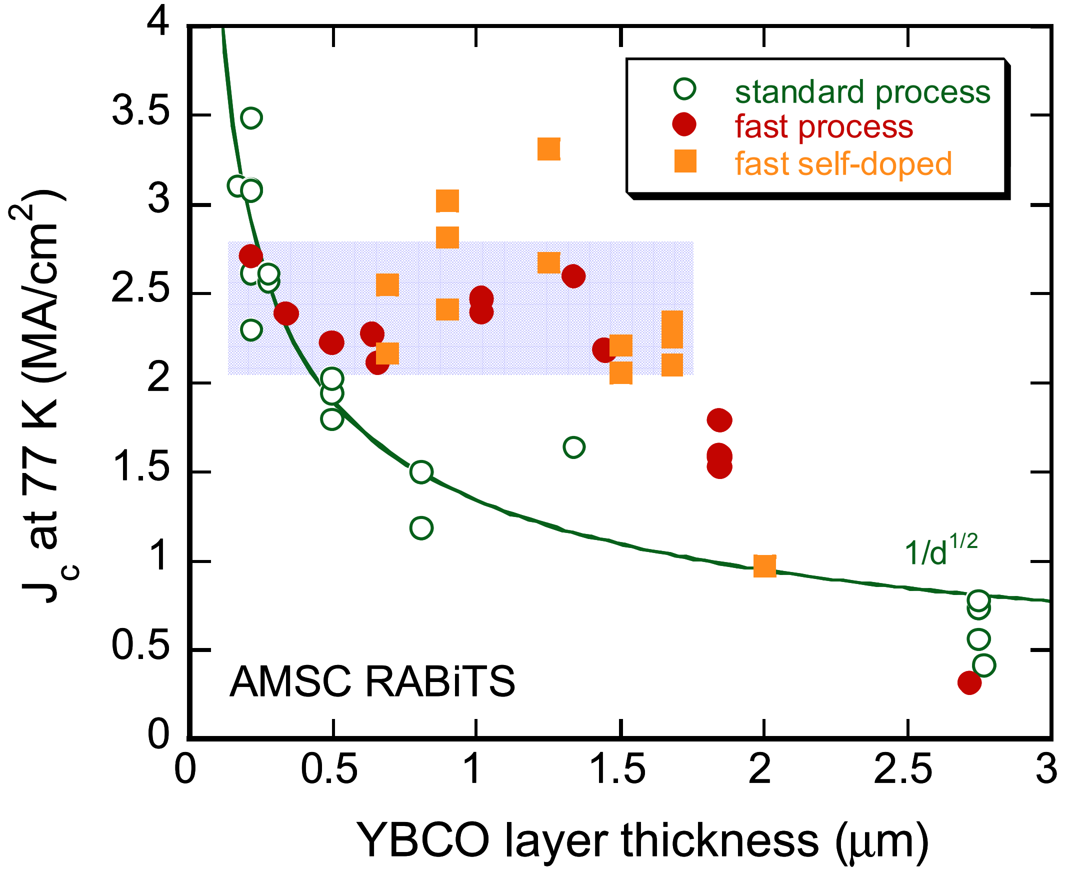
- fast process results in high I_c values for YBCO on RABiTS
  - linear I_c-d relation in the range 0.5-1.3 μm
  - 50% less YBCO delivers same or better I_c than thick films (2.5 μm)

- off-stoichiometric precursors lead to self-doping effects with:
  - strong flux pinning over a wide range of magnetic field angles
  - higher I_c
  - 380-410 A/cm (77K) was obtained for self-doped 1.2-1.7 μm YBCO on AMSC RABiTS

✓ FY2004 milestone of 400 A/cm has been met

Thickness dependence of J_c

Thickness dependence of J_c is drastically reduced with the fast process



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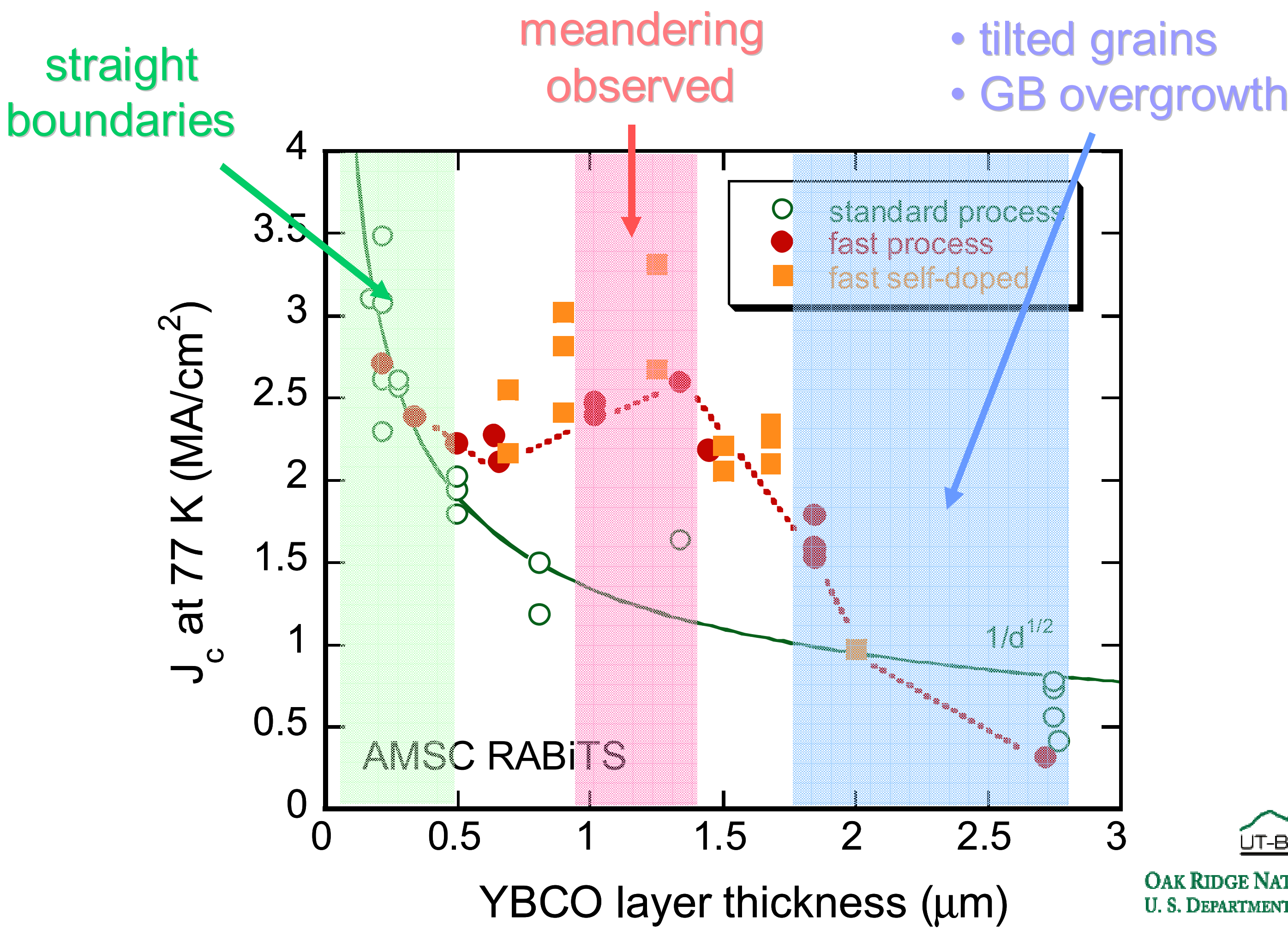
Thickness dependence of J_c exhibits an apparent "hump" for d ≅ 1-1.3 μm (alternative interpretation)

- is the "hump" related to the "meandering" effect?



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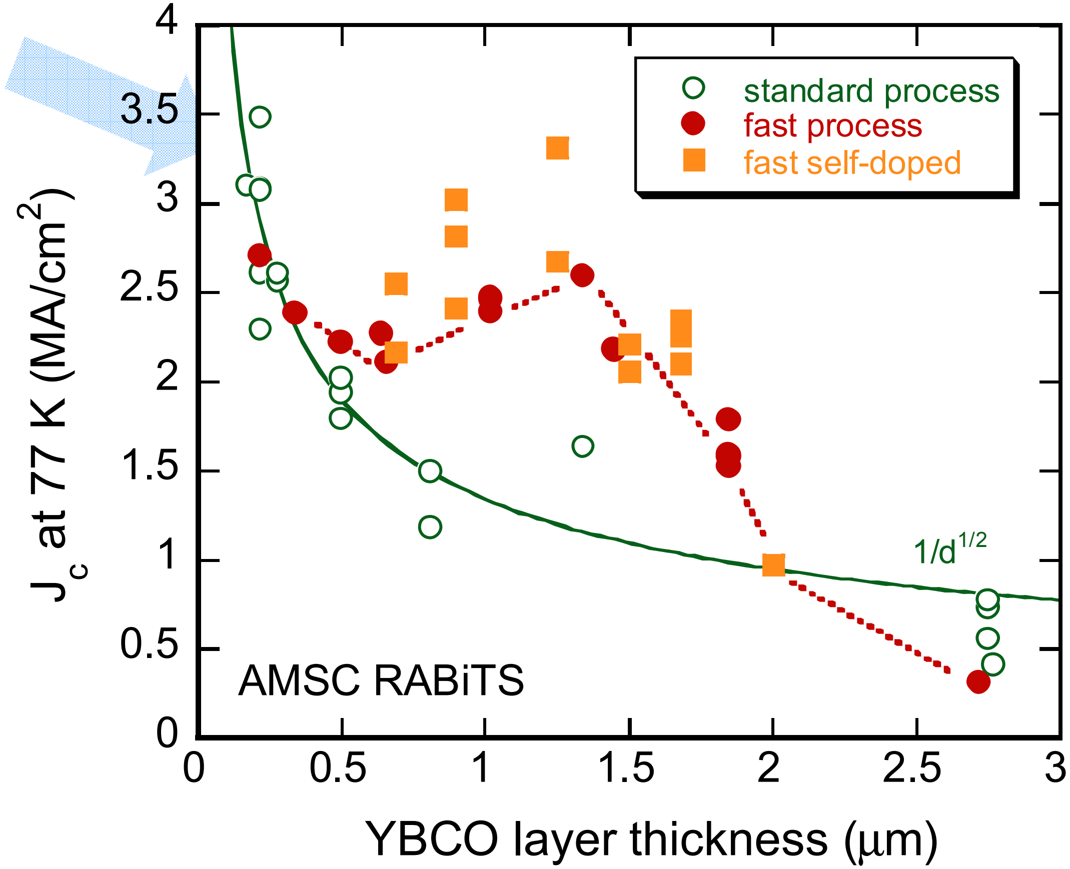
Thickness dependence of J_c exhibits an apparent "hump" for d ≅ 1-1.3 μm (alternative interpretation)

- is the "hump" related to the "meandering" effect?
  - ⇒ new processing opportunities to improve I_c by "GB engineering"
- what is the origin of rise in J_c for small d?



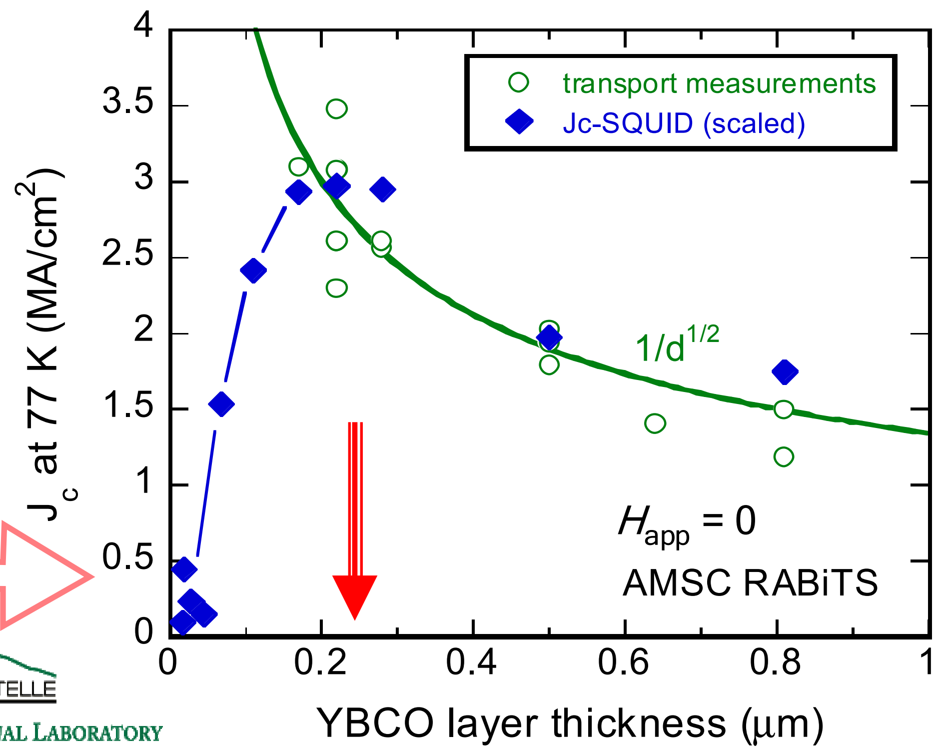
Study of very thin films shows a peak in J_c for YBCO thickness of 0.2-0.3 μm

Anota Ijaduola and Jim Thompson (UTK) *preliminary results*

- ~consistent with earlier results of Jooss et al. for PLD YBCO on STO xtal
- thickness at peak coincides with (1-2) $\lambda_{a,b}$ (penetration depth) → implications ?
- data are being analyzed in collaboration with Gurevich (UW-M)

Superconducting YBCO
< 15 unit cells thick (!)
on metallic substrate

(transport J_c erratic)



research supported by AFOSR-MURI

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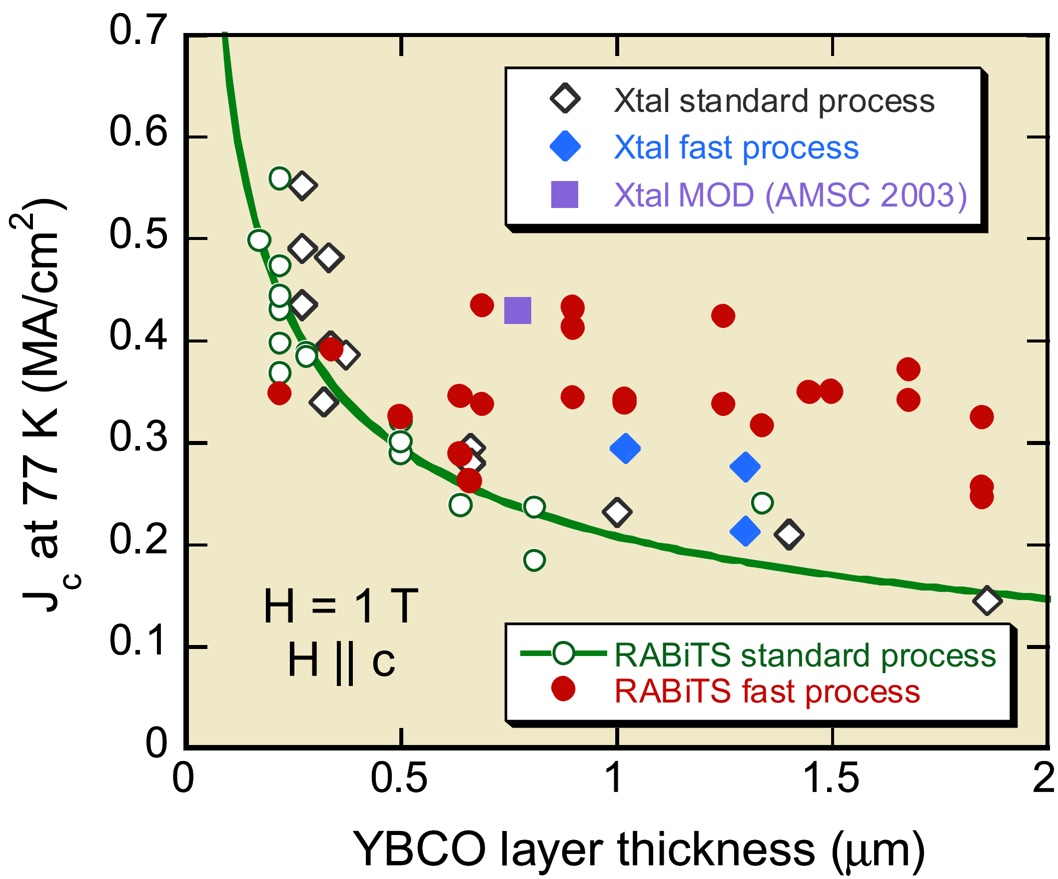
J_c in applied field for YBCO on RABiTS exceeds available data on xtal templates

- similar to LANL observations for PLD YBCO on IBAD-MgO
- is J_c limited by GBs (at H= 1T, 77 K) ?
- reduced percolation effects ?



- FY2004 Results
- FY2004 Performance
- FY2005 Plans
- Technology Integration

FY2004 Results (Scoring Criterion)

- ❖ New processing has been developed for PVD-BaF_2 precursors "killing two birds with one stone"
  - conversion rates > 10 Å/s (duration < 17 min / μm-thickness)
  - fast conversion provides a vehicle for improving I_c

- ❖ Properties of fast processed films:
  - linear relation between I_c and YBCO thickness (0.5-1.3 μm)
  - I_c > 300 A/cm for 1.3 μm YBCO on AMSC RABiTS
  - strong flux pinning with reduced field-angle anisotropy $J_c^{max}/J_c^{min} < 2$
  - homogeneous, non-bimodal microstructure (1.25 μm YBCO)

- ❖ "Self-doping" (non-stoichiometric precursors) improves Ic, flux pinning, and reduces the field-angle anisotropy J_c^{max}/J_c^{min}
  - $I_c \cong$ 400 A/cm for 1.2-1.7 μm YBCO on AMSC RABiTS
  - at present: J_c decreases for d > 1.5-1.8 μm *(not optimized)*

FY2004 Results (Scoring Criterion)

- Unexpected GB structures and modifications in GB network have been visualized by through-thickness EBSD imaging
  - new observation
  - new technique, using laser marking and ion milling

- EBSD and TEM show three variants of GB network as a function of YBCO thickness (suggests a progression in the role of transient liquids)
  - d $\leq$ 0.5 μm—GBs are straight, in registry with substrate—minor liquid
  - d $\cong$ 1 μm—GBs “meander” along substrate GB—intermediate liquid
  - d > 2 μm—complete overgrowth of substrate GBs—excessive liquid

- Alternative variant involving sub-grains observed for MOD-BaF_2 YBCO

FY2004 Results (Scoring Criterion)

- Bimodal structure in thick PVD-BaF_2 YBCO films correlates with J_c
  - bimodal structure: large-grains near substrate, smaller near surface
  - interleaved secondary phases induce tilts in the smaller grains near the surface, reducing J_c
  - bimodal structure without secondary phases permits high J_c
  - absence of a bimodal structure in fast-processed 1.25 μm high-I_c film suggests reduced liquid phase generation
- Unique characteristics of ex situ grown YBCO films
  - laminar grain structure
  - GB meandering through-thickness / GB overgrowth
- Ubiquitous observation of pores in MOD and PVD-BaF_2 YBCO
  - pores are a consequence of and possibly aid the conversion process
  - pores do not inhibit the achievement of high I_c

FY2004 Performance (Scoring Criterion)

Goal:
Obtain 10 Å/s growth rate with PVD-BaF_2 precursors

⇒ Actions

- ✓ Developed a "fast" process that ties together precursor preparation history and conversion parameters
- ✓ Measured growth rates up to 13 Å /s by in situ XRD in a vacuum conversion system
- ✓ Produced YBCO films with I_c >300 A/cm in a standard 1-atm furnace using growth rates of 6-12 Å/s

FY2004 Performance (Scoring Criterion)

Goal:
Increase I_c in PVD-BaF_2 YBCO films on CC substrates to values > 400 A/cm (77K)

⇒ Actions

- ✓ Performed studies to improve processing of 1-2 μm thick YBCO coatings on RABiTS
- ✓ Established a linear relation between I_c and YBCO thickness in fast processed films
- ✓ Applied results from flux pinning study to further improve I_c
  - $I_c \cong$ 410 A/cm (1.25 μm YBCO)
  - $I_c \cong$ 390 A/cm (1.7 μm YBCO)

FY2004 Performance (Scoring Criterion)

Goal:
Study the microstructure of PVD BaF_2 YBCO films by TEM to determine the role of transient liquids in the conversion process

⇒ Actions

- ✓ Performed analytical TEM on variable thickness films deposited on RABiTS with low and high J_c
- ✓ Observed different variants of the bimodal structure in thick PVD-BaF_2 YBCO
- ✓ Identified secondary phase layers as a current limiting mechanism
- ✓ Compared microstructures of "standard", "fast process", and AMSC MOD films and identified unique characteristics of ex situ YBCO

FY2004 Performance (Scoring Criterion)

Goal:
Study current limiting mechanisms in high-I_c PVD and MOD-BaF_2 YBCO coated conductors

⇒ Actions

- ✓ Developed a technique to study through-thickness GB networks
- ✓ Applied the new technique to look at 3-dimensional GB networks in PVD-BaF_2 YBCO on RABiTS and IBAD-YSZ
- ✓ Showed that the new technique is also applicable to MOD-BaF_2 YBCO
- ✓ Started bi-crystal experiments to study correlations between 3-dimensional GB structures and J_c

FY2004 Performance (Scoring Criterion)

Goal (added objective):
Perform research in the context of the WDG to elucidate the origin of, and improve flux pinning in PVD-BaF_2 YBCO coated conductors

⇒ Actions

✓ Performed measurements of J_c as a function of H field, temperature, and field angle to build a database.

✓ Studied effects from variable precursor composition on flux pinning properties ("self-doping" effects)

❑ WDG plan to study effects of R doping in PVD-BaF_2 YBCO was deferred because of budgetary constraints

Goal:
Develop a compatible buffer layer architecture for the PVD-BaF_2 process on IBAD-MgO template

⇒ Actions

❑ A limited effort was made.
Needed in-depth study was deferred because of budgetary constraints

FY2005 Plans (Scoring Criterion)

- ❖ Study how the liquid-mediated growth can be controlled to improve the structure and properties of grain boundaries (GB) in 1-2 μm ex situ YBCO coatings on RABiTS and IBAD templates
  - optimize J_c by variation of conversion and precursor parameters
  - use TEM and EBSD at various levels within a film to study GB structure and meandering
  - perform bi-crystal studies to relate J_c(GB) to 3-dimensional variations in the GB structure
- ❖ Identify the composition of transient liquids in the conversion of PVD-BaF_2 precursors
  - trap liquids by quenching
  - use analytical TEM to study structure-chemistry-processing relations

FY2005 Plans (Scoring Criterion)

- Study effects of rare-earth (R) substitutions for Y using the newly developed fast process
  Goals:
  - explore new opportunities to modify the mediated growth to optimize the GB network/structure, improve J_c, flux pinning
  - WDG related task
  - initial studies: 100% substitution $\rightarrow$ RBCO (several R elements)
  - desired direction: partial substitution $\rightarrow$ (Y,R)BCO or (R_1R_2)BCO
  - capital investment is needed to install a fourth evaporation source in precursor deposition chamber (deferred from FY2004)
  - properties will be compared to YBCO to evaluate benefits

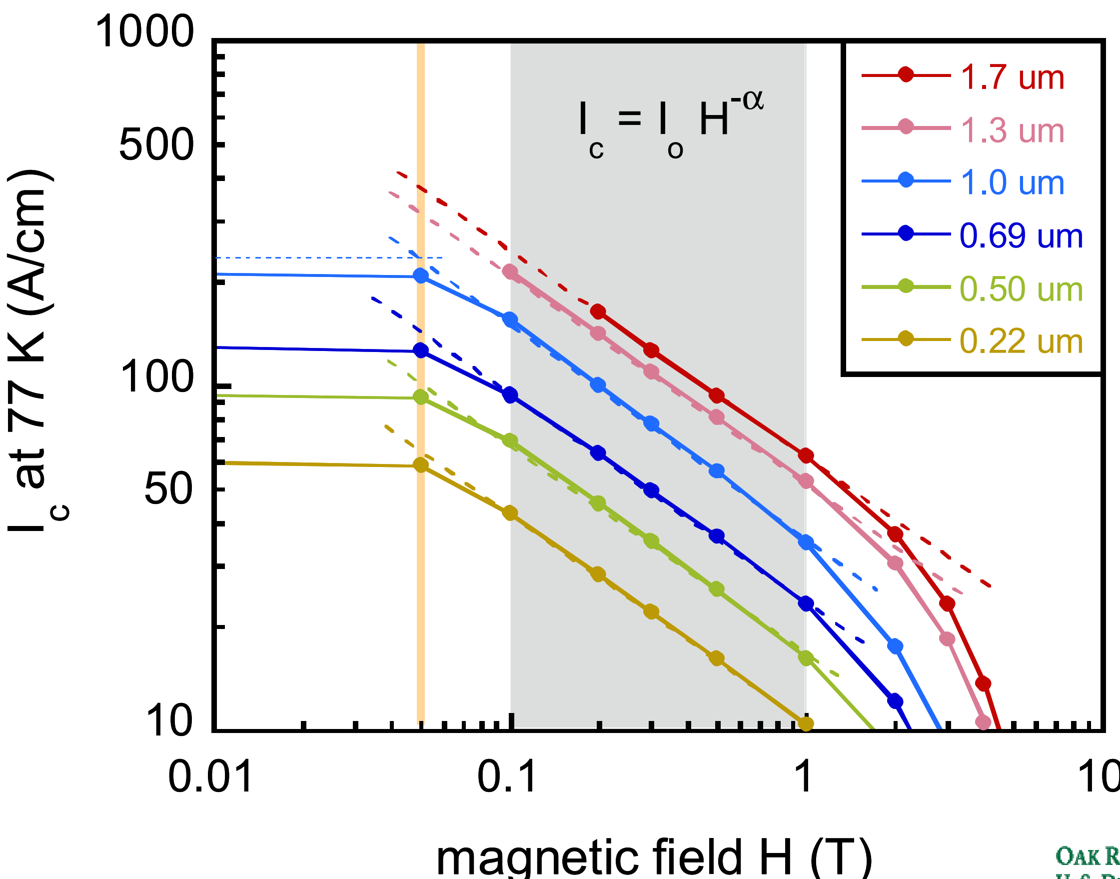
Research Integration (Scoring Criterion)

- This research group represents a synergistic effort between two national laboratories, a leading university research group, and an industry leader in coated conductor research and development
- Each partner brings unique expertise to the collaboration
- Contact is maintained through frequent phone calls, email, and in-person meetings
  - WDG provides a forum to meet as a team and with AMSC
  - information from team research is shared with AMSC in a timely manner
- Interactions with other institutions leverage the research
  - ICMAB, Barcelona, Spain (thickness dependence of J_c^{intra}, J_c^{inter})
    - 2 Spanish students at ORNL last summer
  - NIST-Gaithersburg (phase development)
  - NIST-Boulder (strain effects: thick YBCO on RABiTS)

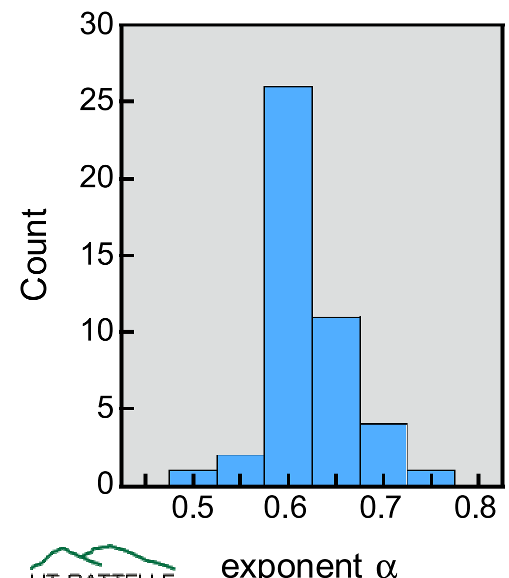
Thanks !

I_c increases with YBCO thickness over a wide range of applied magnetic fields

Use extrapolation of linear $I_c(H)$ dependence in log-log representation to estimate $I_c(0)$ of thick films (beyond experimental range)



exponent $\alpha \cong 0.6$ for most films



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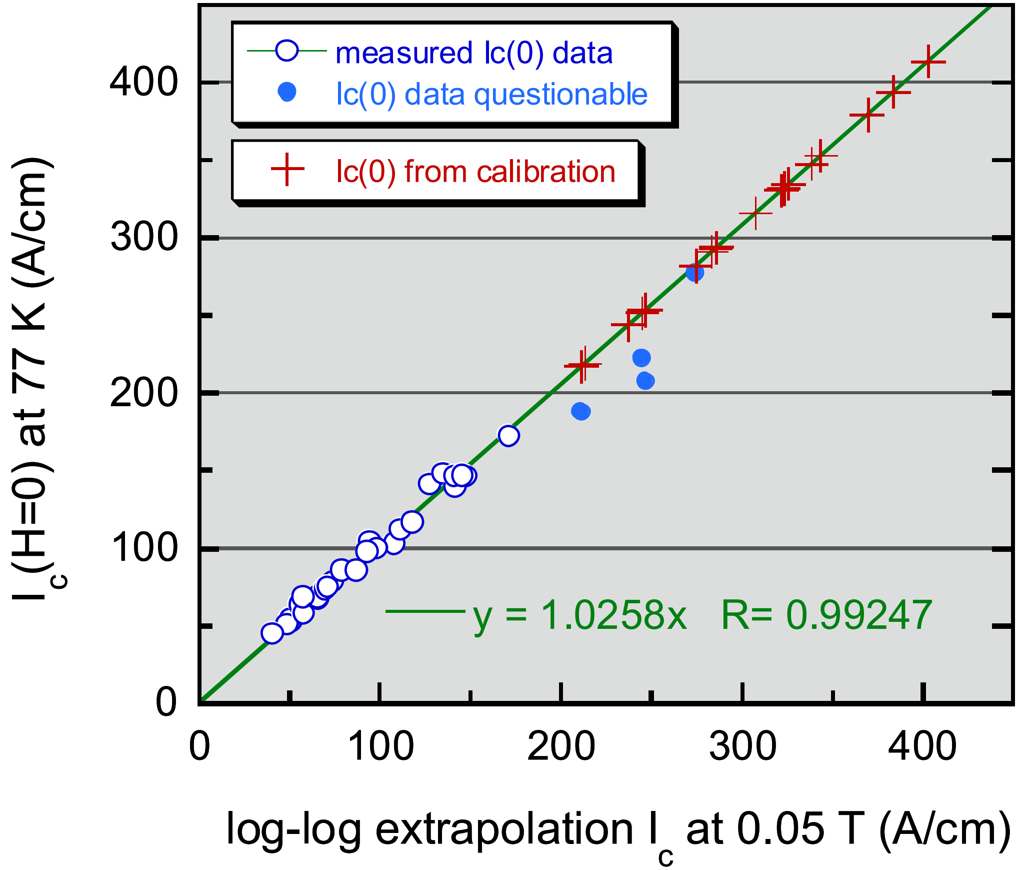
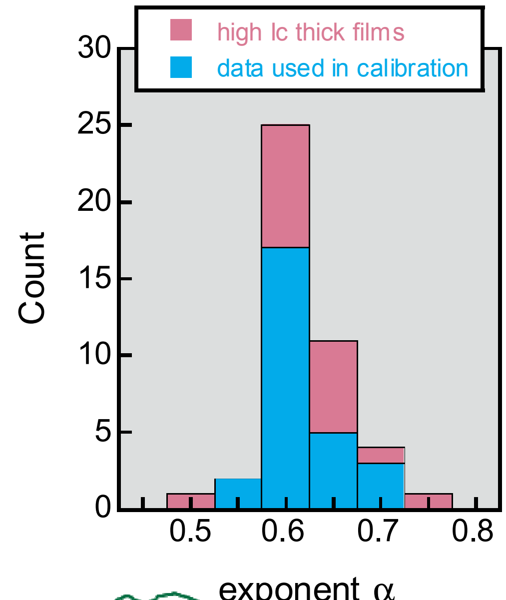
Log-log extrapolation provides a meaningful estimate of self-field I_c beyond measurement range

- robust demonstration of $I_c(0)$ > 350 A/cm (d ≅ 1.2-1.7 μm)
- approach is more systematic than conversion from single $I_c(H)$ value





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